

Utilidad del monitoreo sísmico en minas subterráneas: validación de modelos geomecánicos y comprensión de la mecánica de estallidos de roca

***Frank Calixto
Institute of Mine Seismology***





Parte 1: Validación de los modelos geomecánicos

Commission de la Carte Géologique du Monde / Commission for the Geological Map of the World



WORLD STRESS MAP



2009 - 2nd edition, based on the WSM database release 2008
Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences

Authors

Oliver Heidbach, Mark Tingay, Andreas Barth, John Reinecker, Daniel Kurfeß, and Birgit Müller



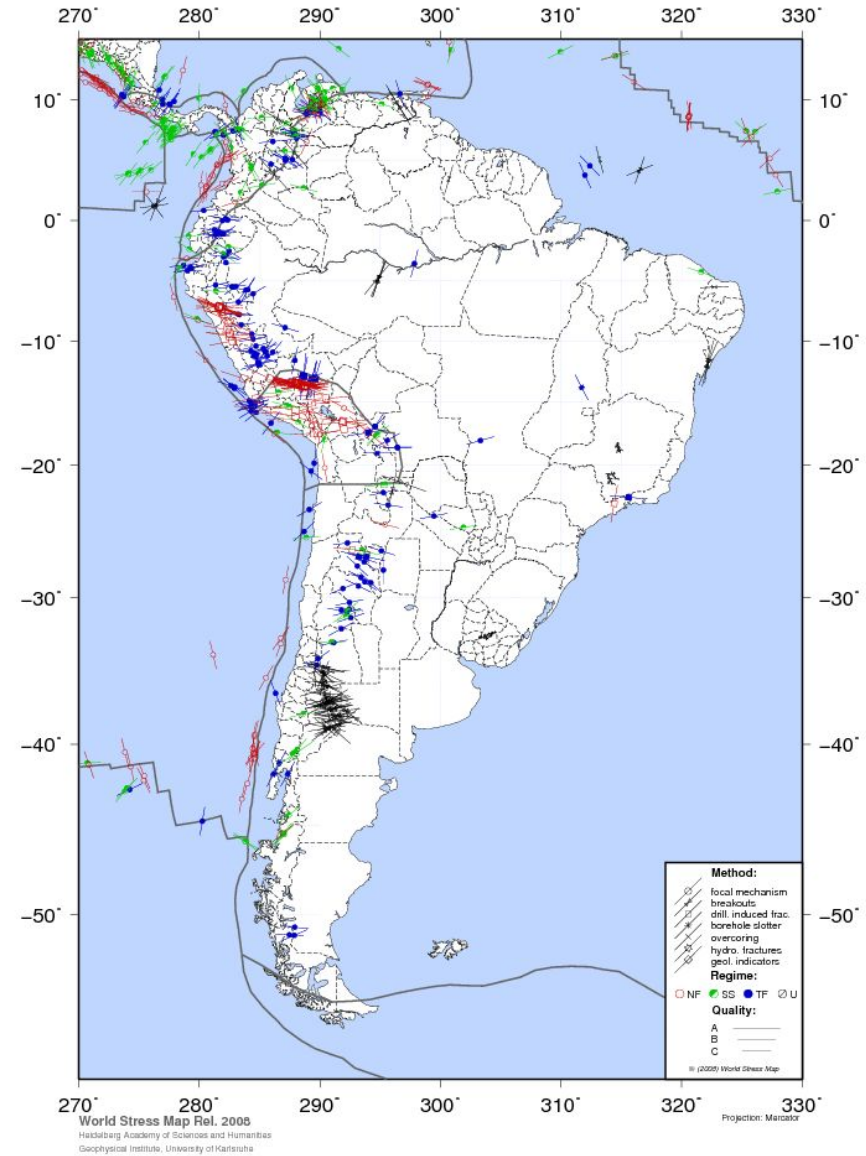
Explanatory Text

The World Stress Map (WSM) is the global compilation of information on the present-day stress field in the Earth's crust. It is a collaborative project between academia, industry and government that aims to characterize the crustal stress pattern and to understand the sources of tectonic stress. The project commenced in 1986 as a part of the International Lithosphere Program, under the leadership of Mary Lou Zoback. From 1995-2008, the WSM was a project of the Heidelberg Academy of Sciences and Humanities. Since 2009 it is maintained and further developed at the Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences.

All stress information is recorded in a standardized format and quality-ranked for reliability and comparability on a global scale. The stress maps on this poster display A-C quality stress data in the upper 40 km of the Earth's crust from the WSM database release 2008. Focal mechanism solutions determined as being potentially unreliable (labelled as Possible Plate Boundary Events in the database) are not displayed. Further detailed information on the quality ranking, guidelines for various stress indicators, and software for stress map generation can be found on the WSM website at www.world-stress-map.org.

The stress maps display the maximum horizontal compressional stress S_H

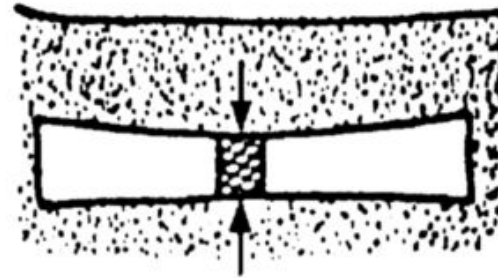
Method	Quality	Stress Regime
focal mechanism	A — S_H is within $\pm 15^\circ$	Normal faulting
breakouts	B — S_H is within $\pm 20^\circ$	Strike-slip faulting
drill. induced frac.	C — S_H is within $\pm 25^\circ$	Thrust faulting
overcoring		Unknown regime
hydro. fractures		
geol. indicators		
Data depth range 0-40 km		
	<p>normal faulting regime $S_V > S_H > S_h$</p>	<p>strike-slip regime $S_H > S_V > S_h$</p>
		<p>thrust faulting regime $S_H > S_h > S_V$</p>



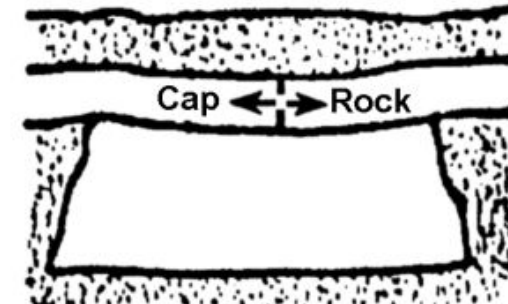
6 formas posibles de ocurrencia de eventos sísmicos en minas (Hasegawa et al., 1989)



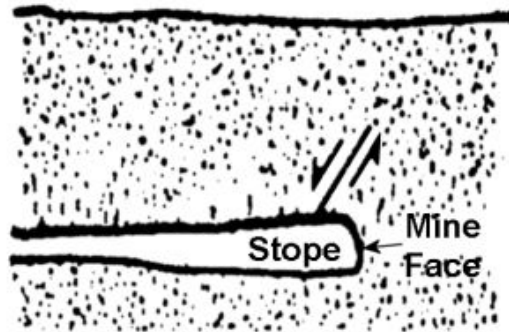
(a) CAVITY COLLAPSE



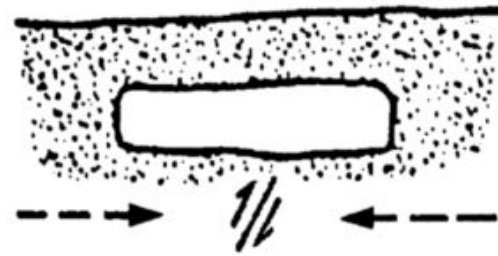
(b) PILLAR BURST



(c) TENSIONAL FAULT



(d) NORMAL FAULT

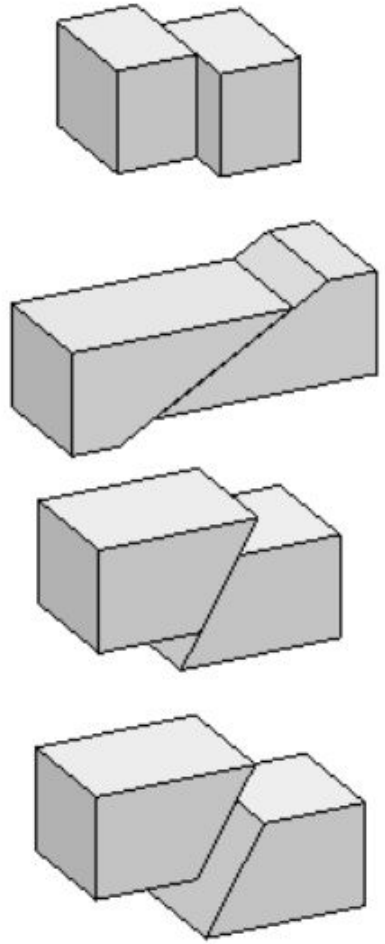
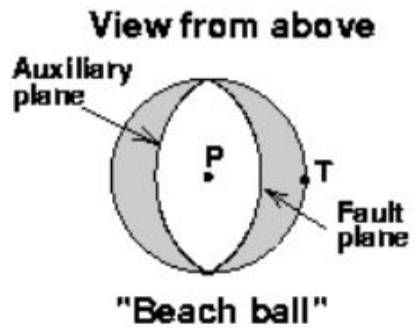
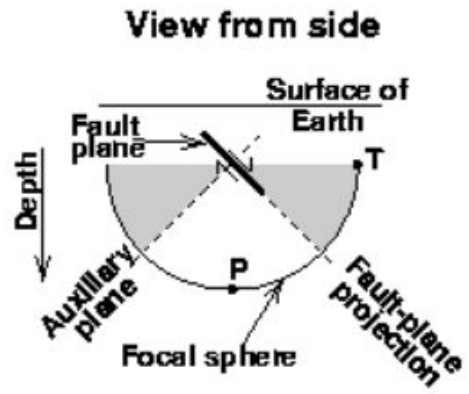


(e) THRUST FAULT

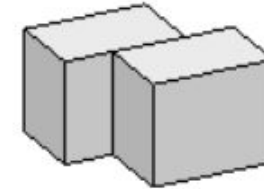


SHALLOW
(NEAR HORIZONTAL)
(f) THRUST FAULTING

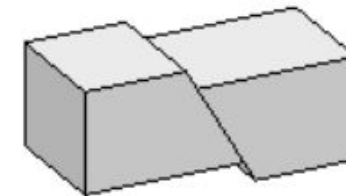
Mecanismos de fuentes sísmicas sin cambio volumétrico



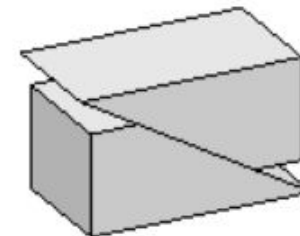
Strike slip



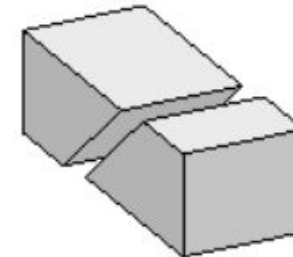
Normal



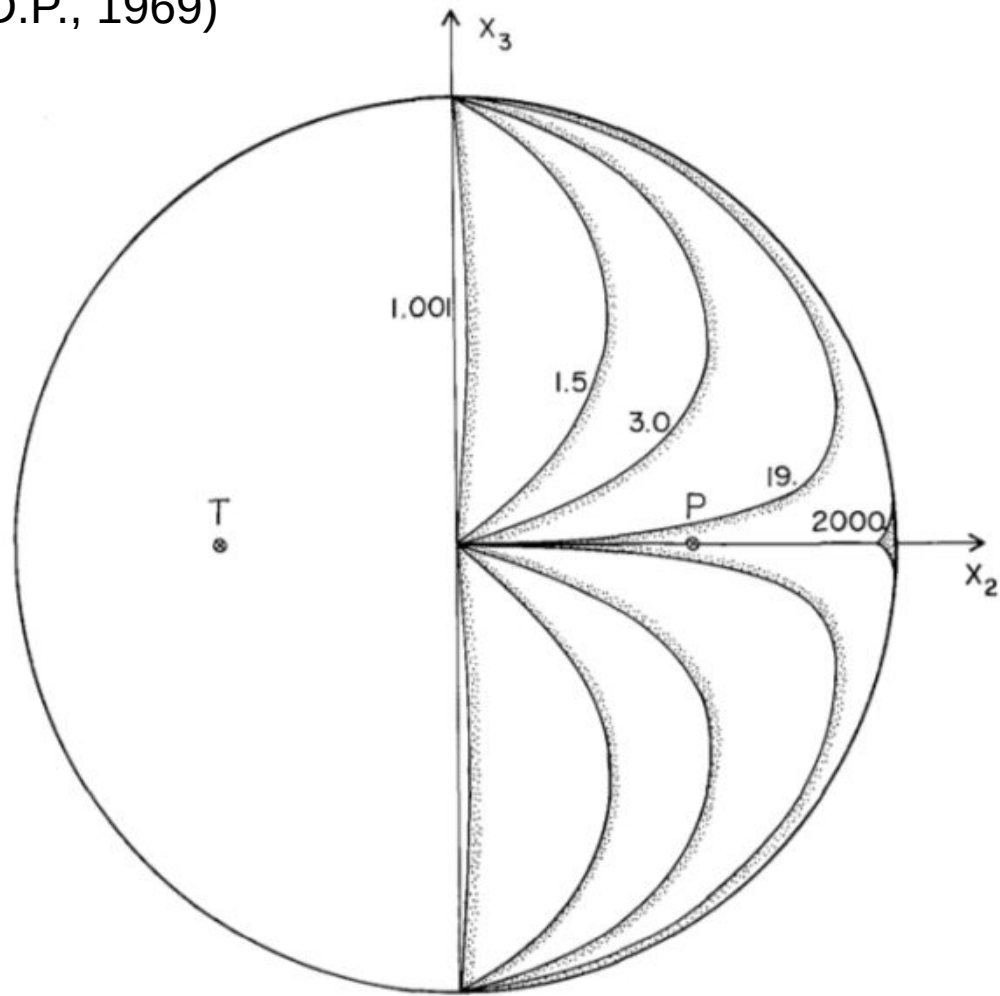
Reverse



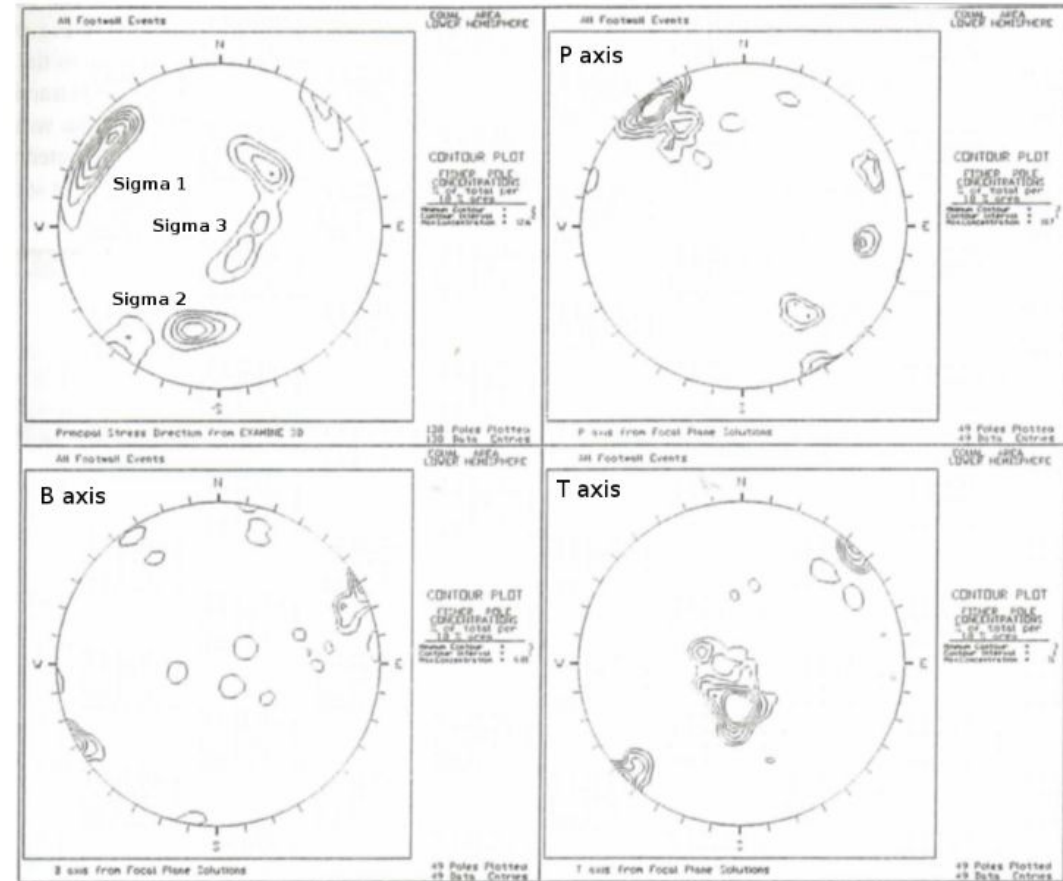
Oblique reverse



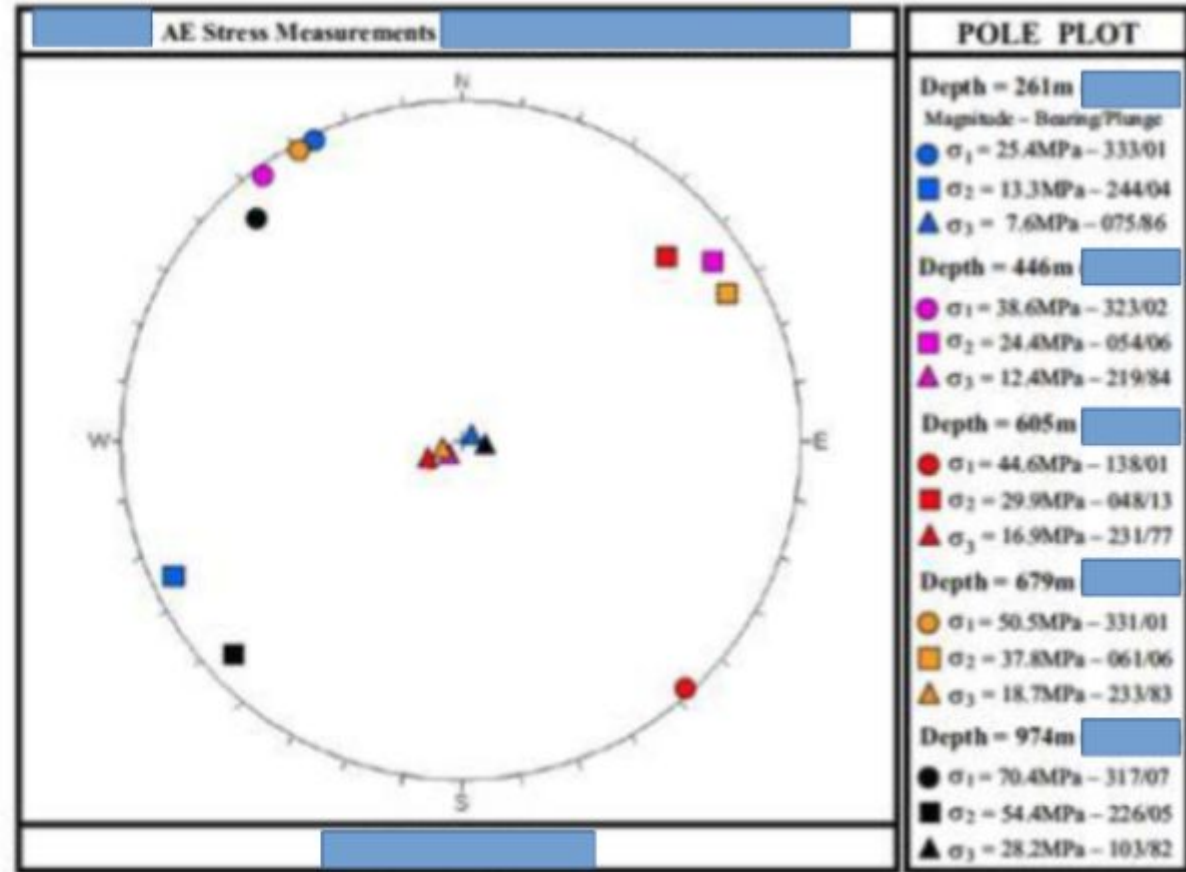
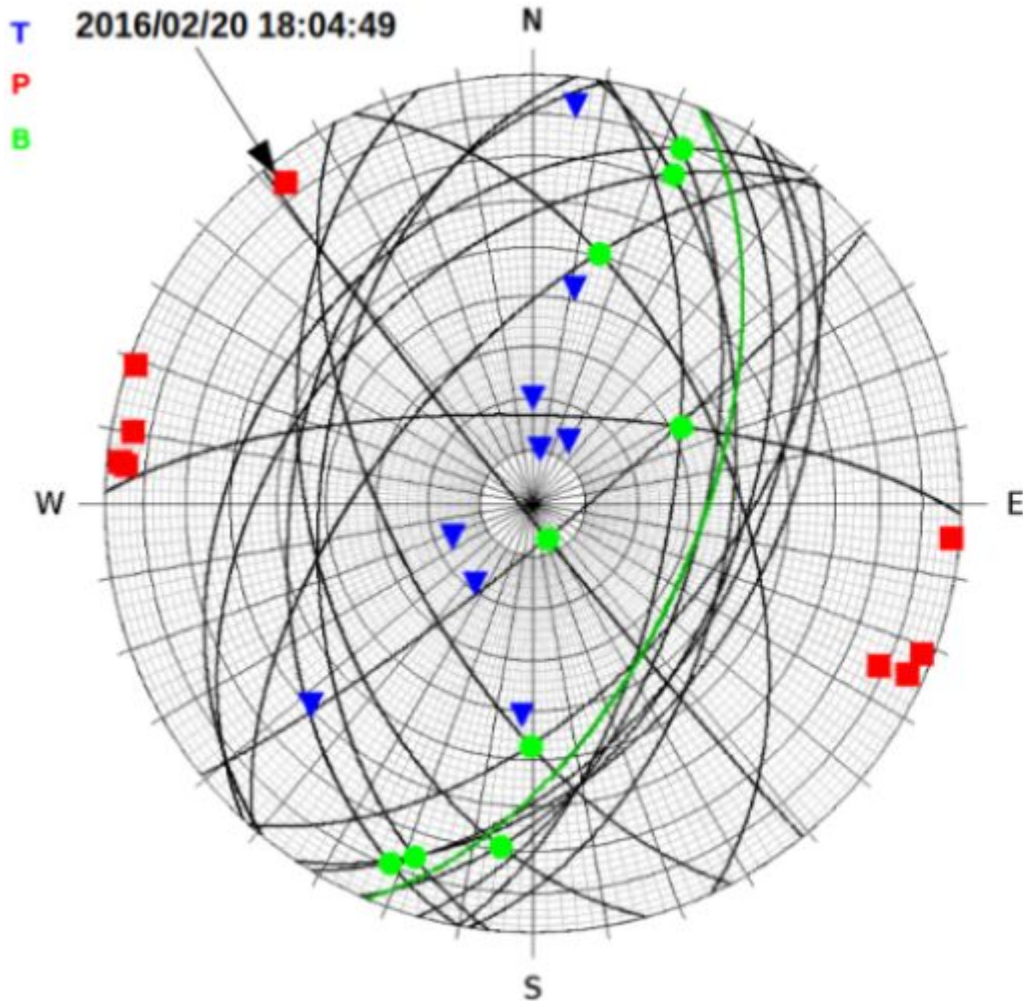
La relación entre eventos en planos de falla y la dirección de los esfuerzos principales (McKenzie D.P., 1969)



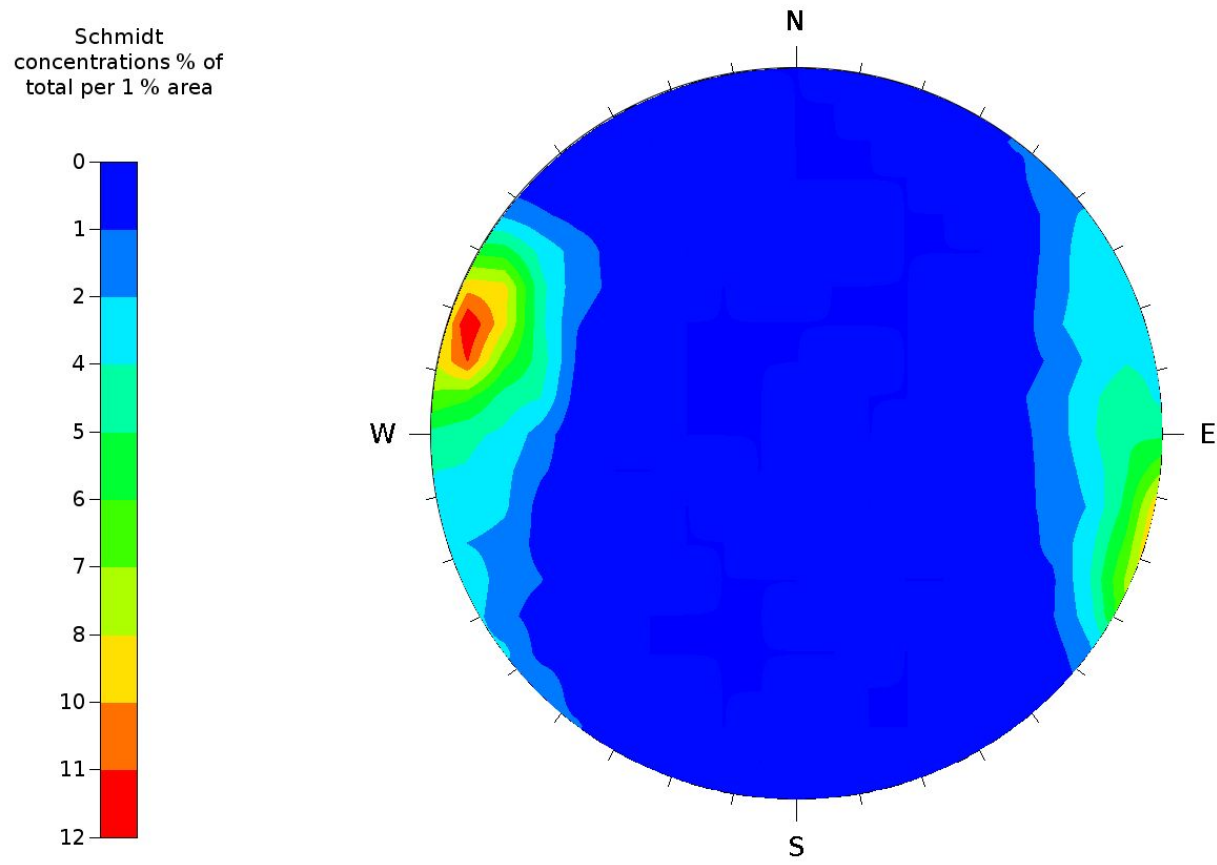
Bawden (1993)



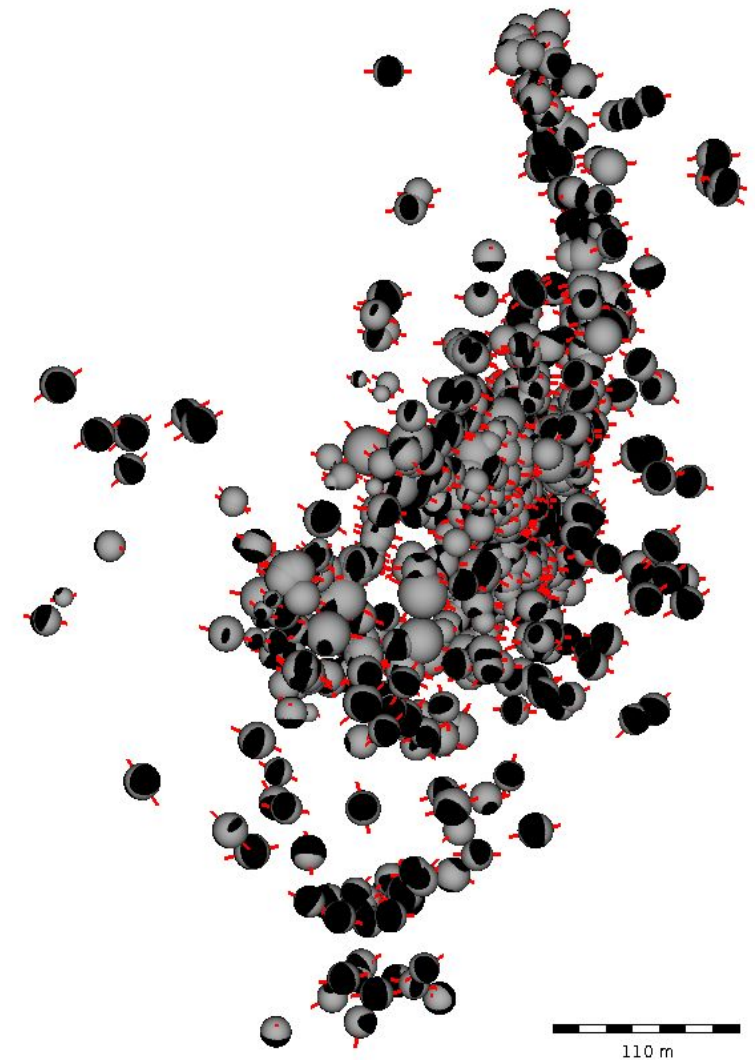
Ejemplo mina 1, comparación con mediciones de esfuerzos in situ



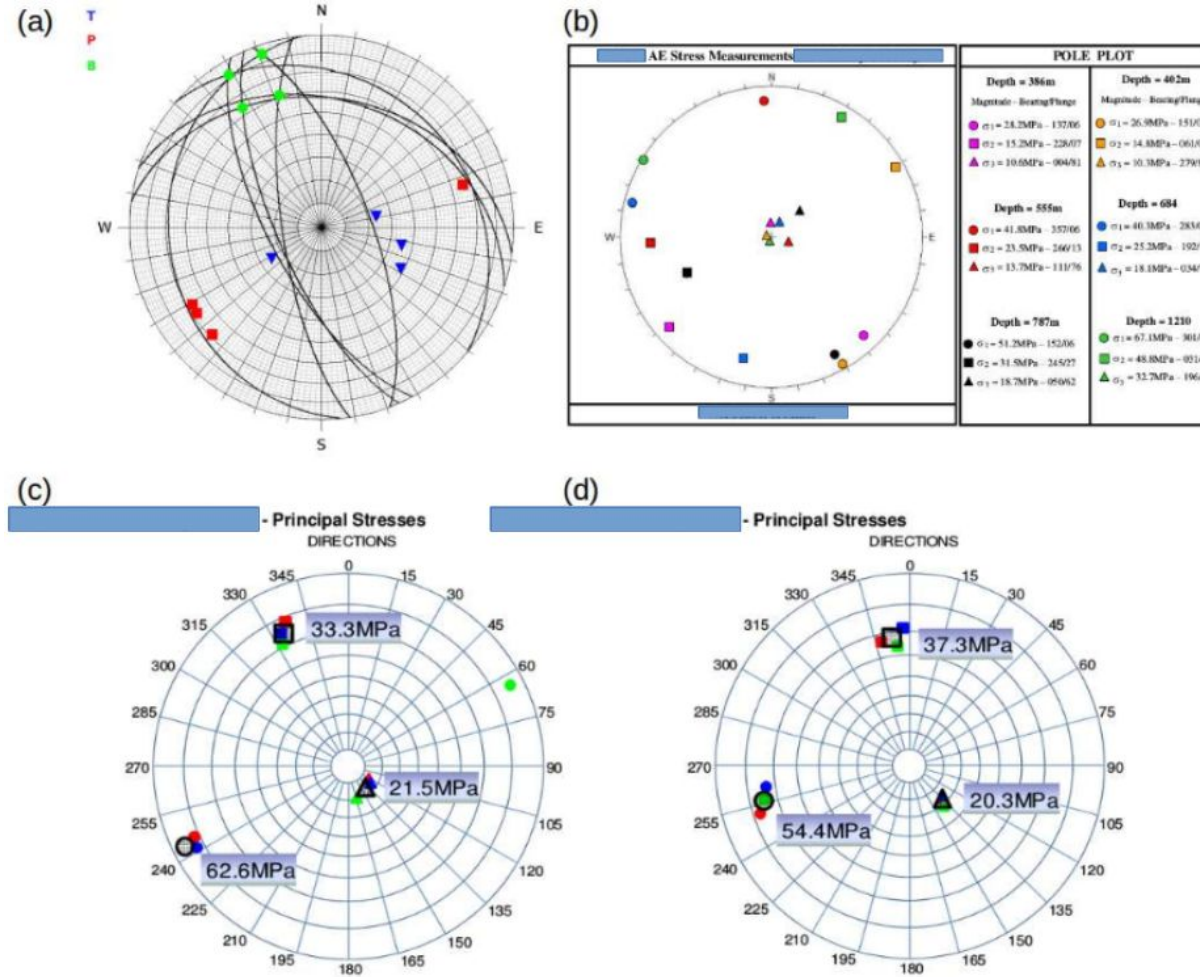
Ejemplo mina 1, comparación con mediciones de esfuerzos in situ



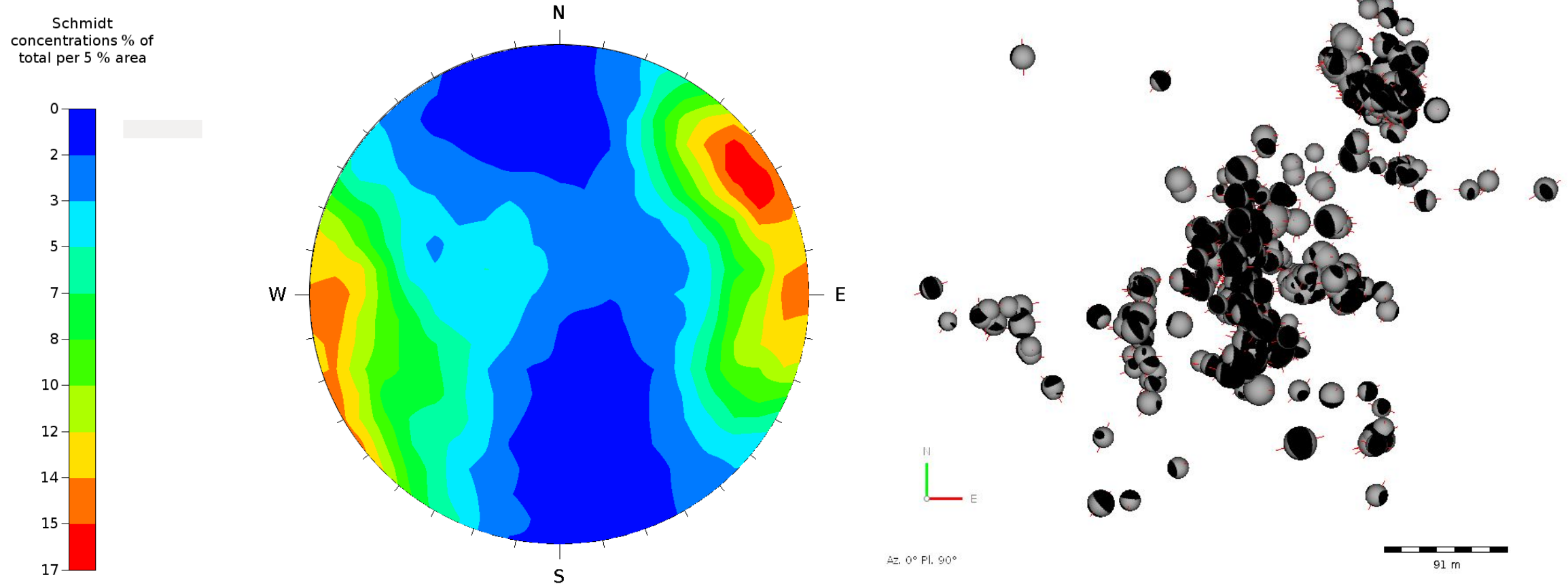
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Az. 0° Pl. 90°



Ejemplo mina 2, comparación con mediciones de esfuerzos in situ

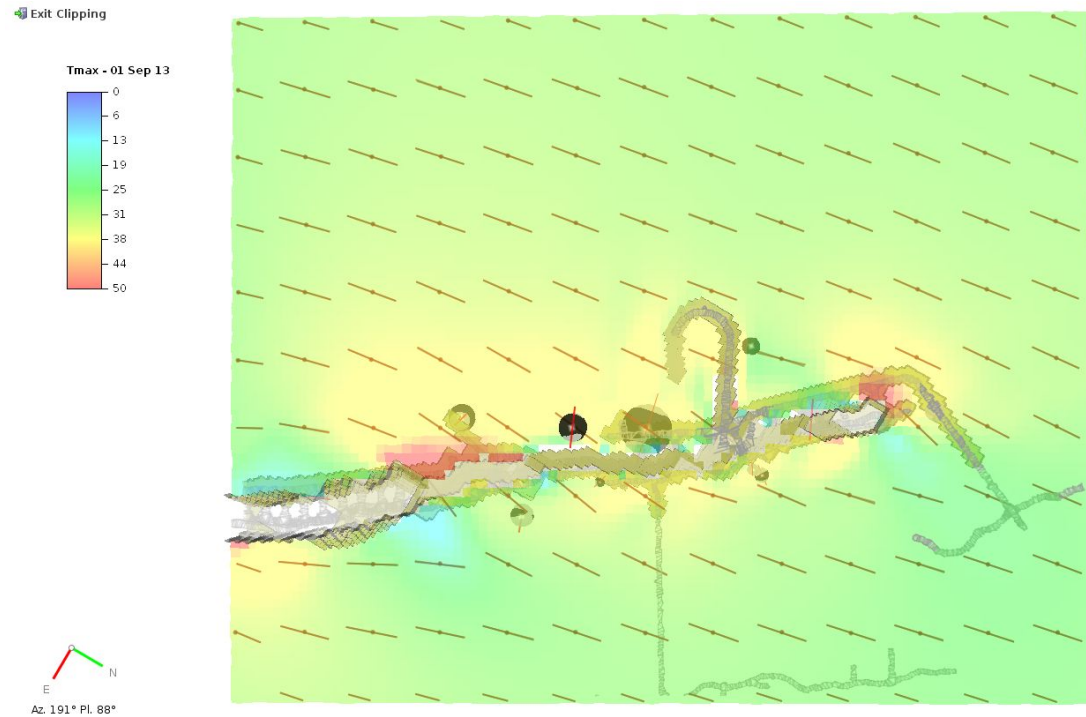


Ejemplo mina 2, comparación con mediciones de esfuerzos in situ

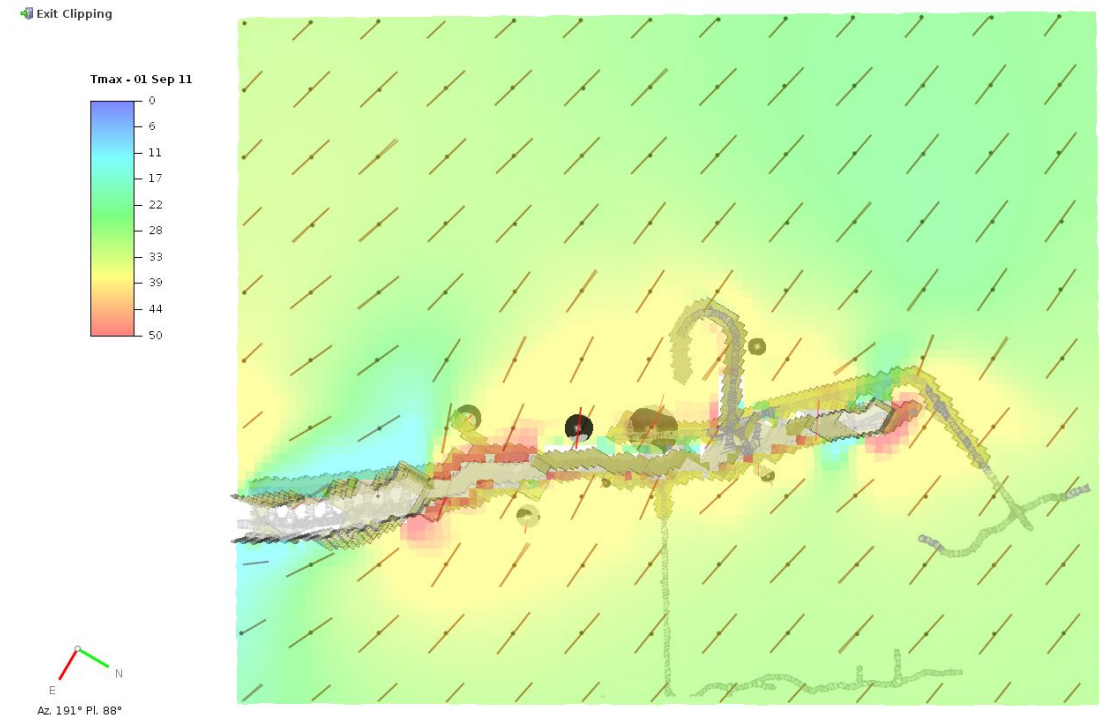


Ejemplo mina 3, comparación con modelamiento

Nivel 1: con esfuerzos in situ

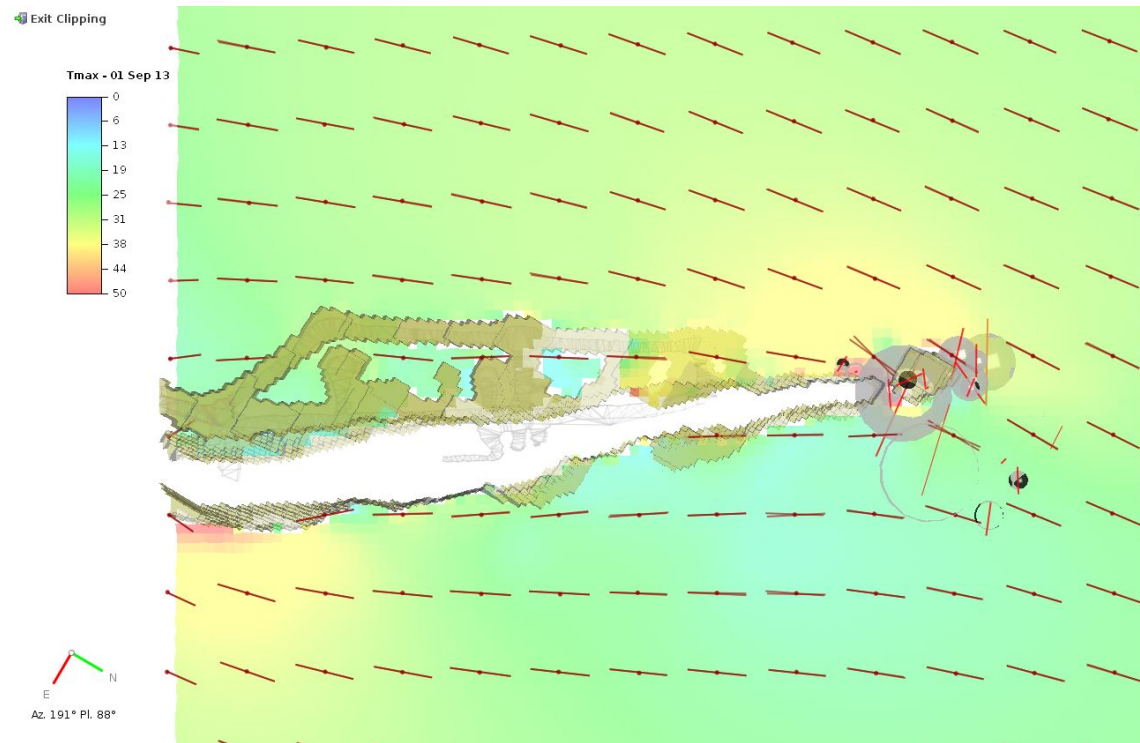


Nivel 1: con esfuerzos inferidos

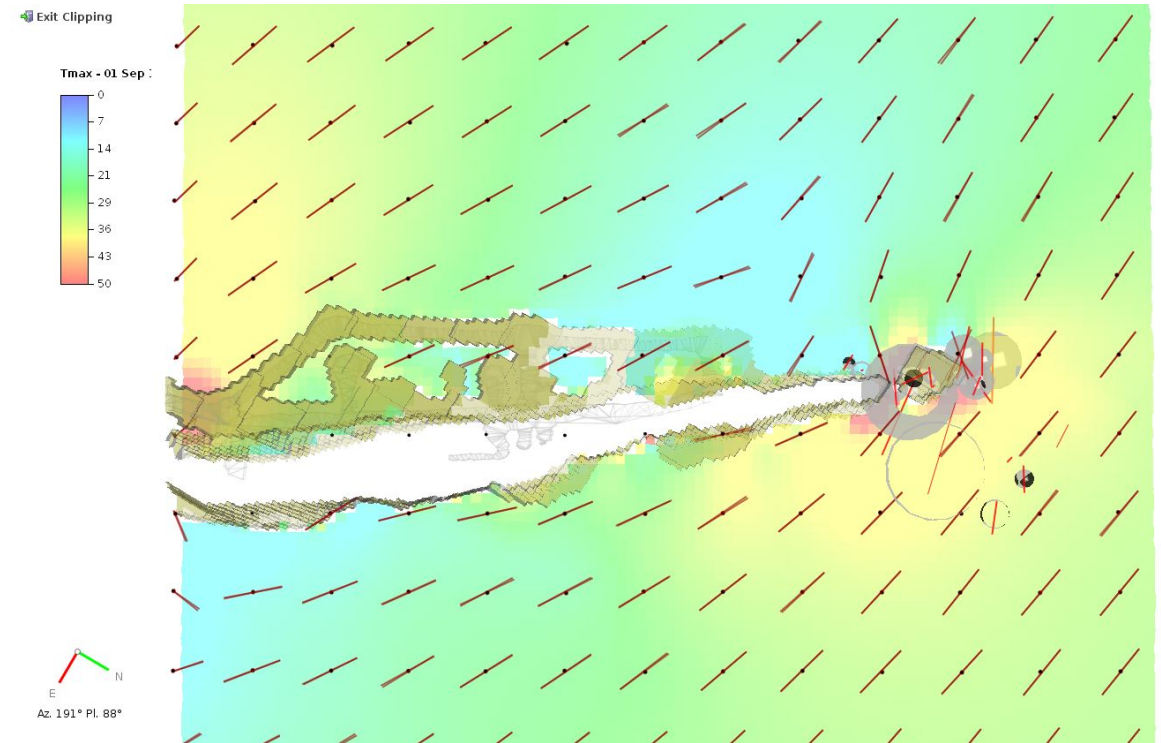


Ejemplo mina 3, comparación con modelamiento

Nivel 2: con esfuerzos in situ

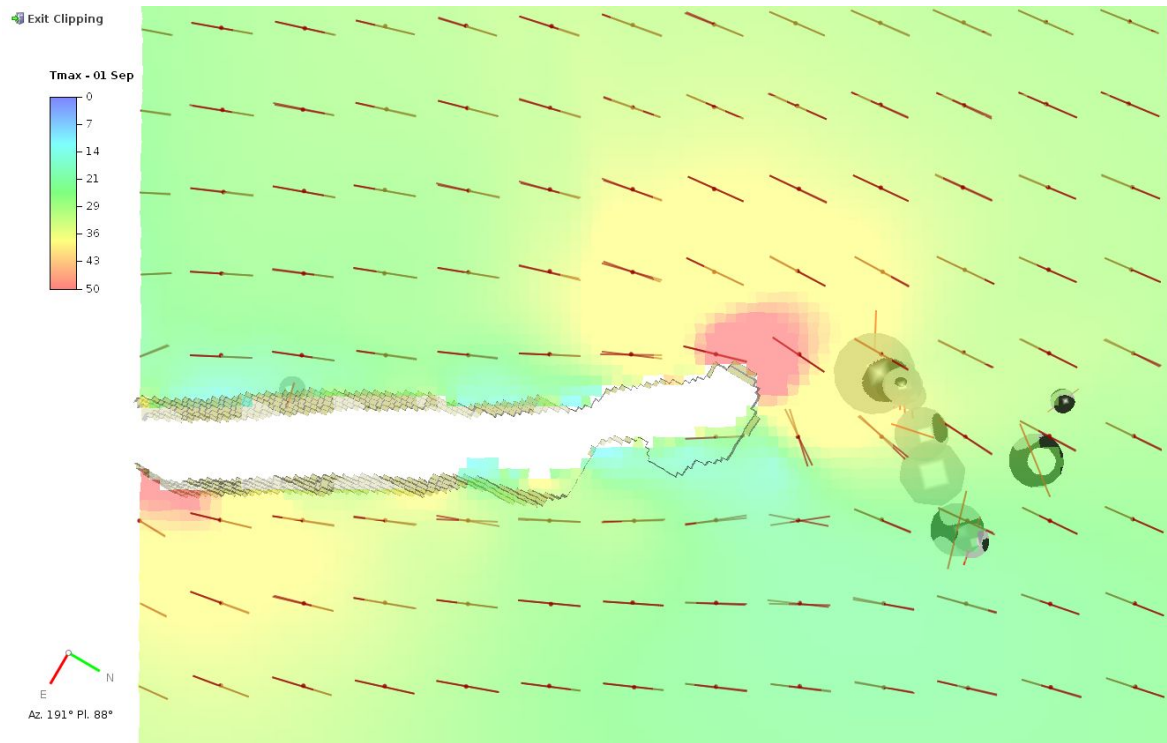


Nivel 2: con esfuerzos inferidos

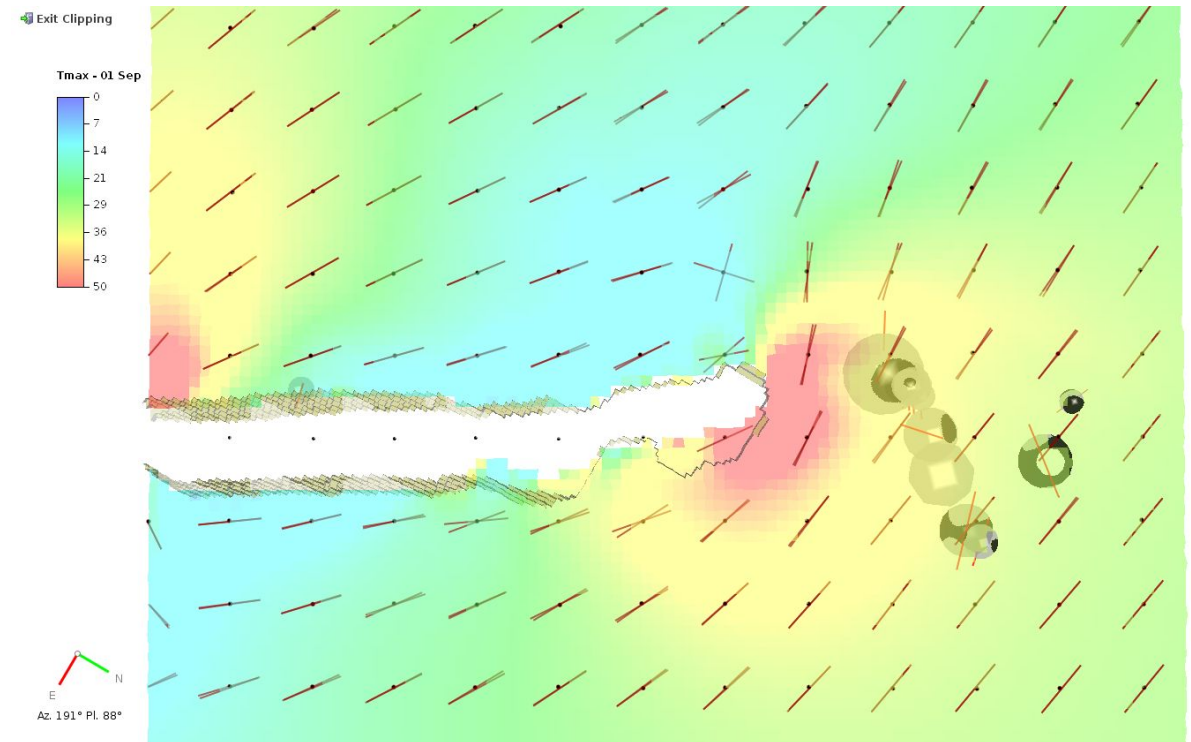


Ejemplo mina 3, comparación con modelamiento

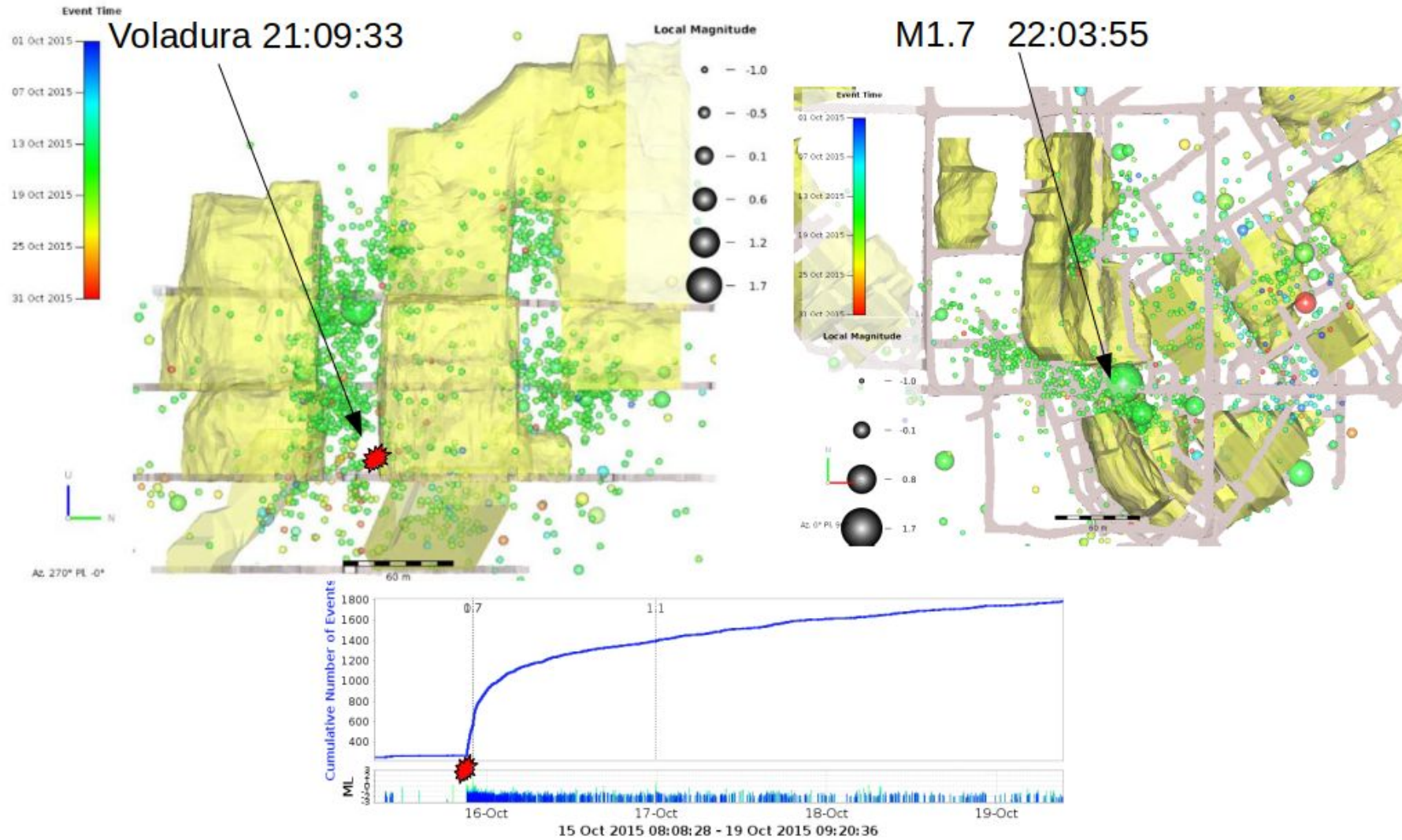
Nivel 3: con esfuerzos in situ



Nivel 3: con esfuerzos inferidos

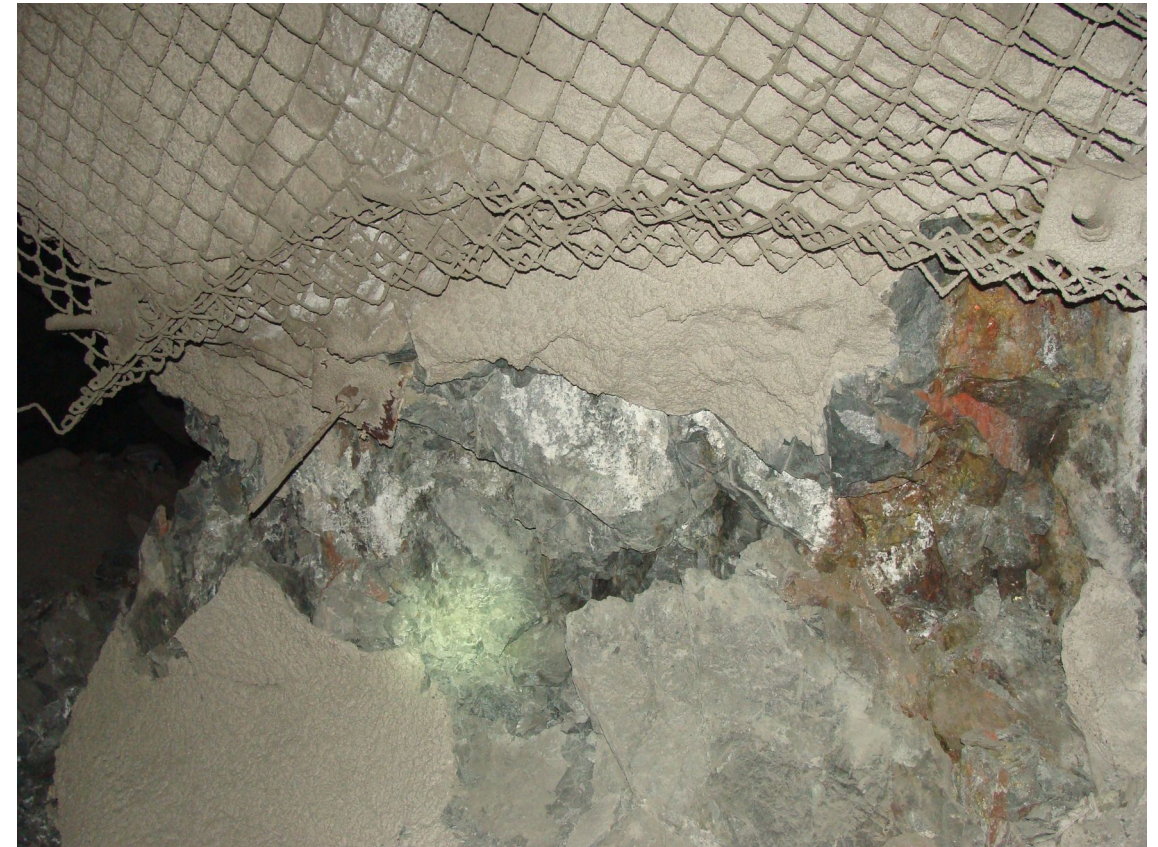
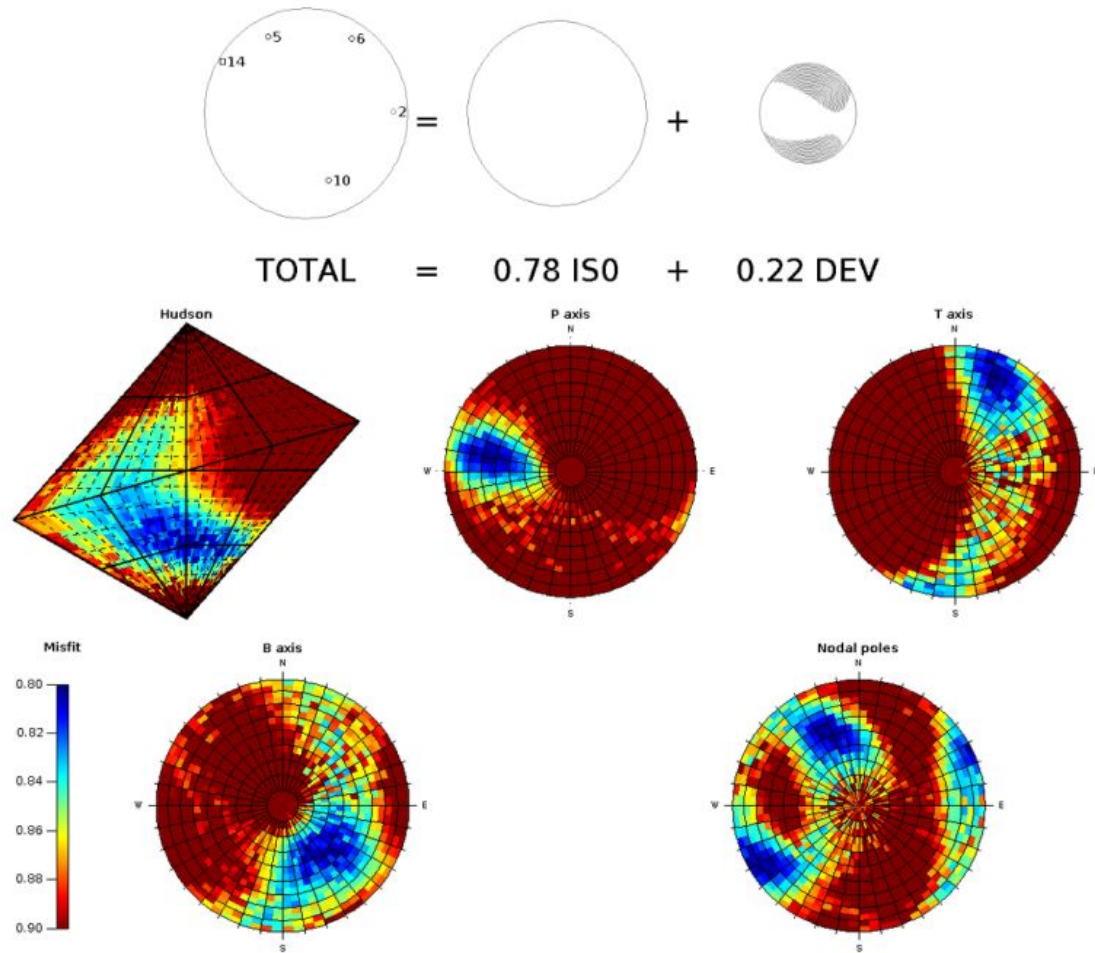


Ejemplo mina 3, inferir direcciones de esfuerzos en 3D y cambio temporal

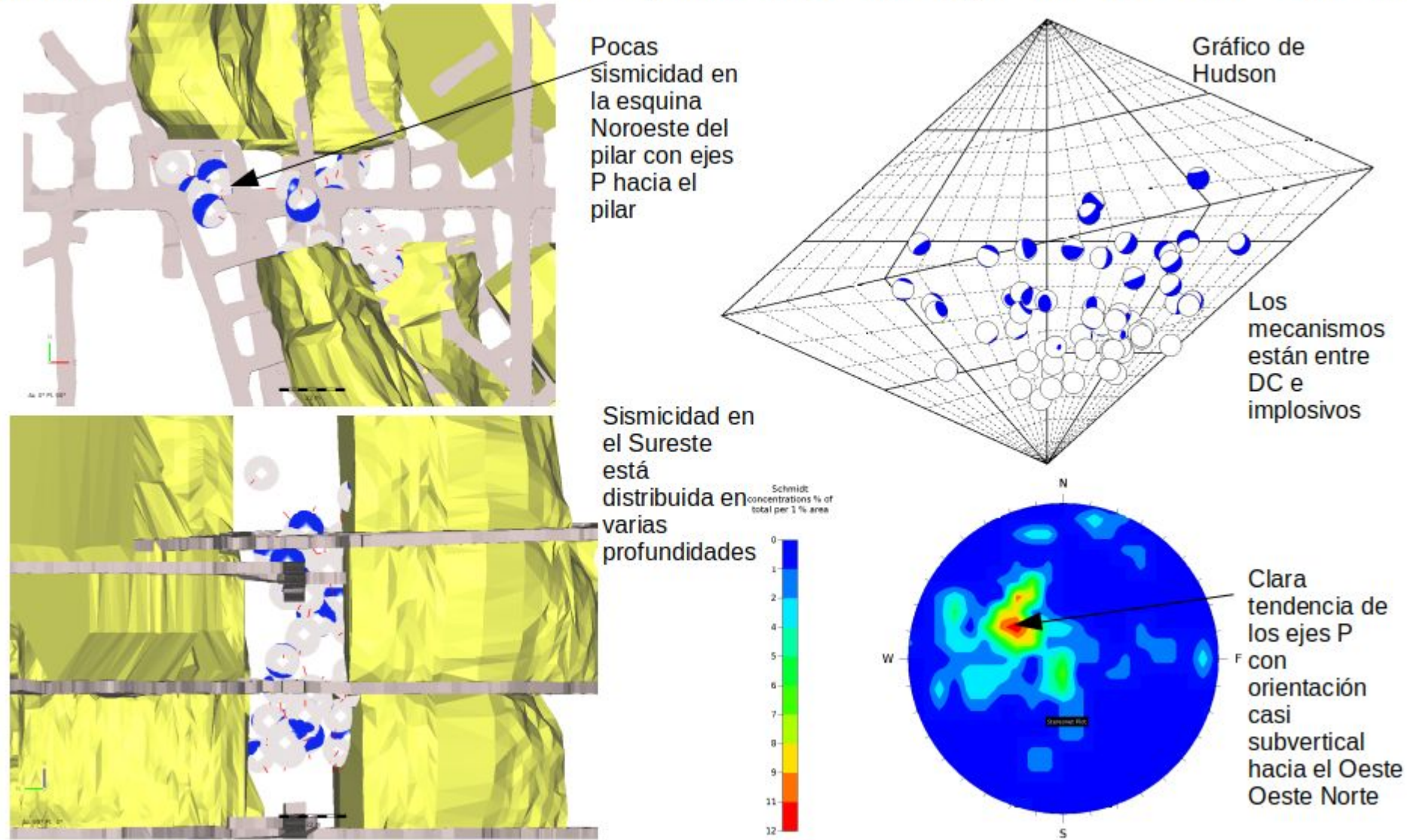


Ejemplo mina 3, inferir direcciones de esfuerzos en 3D y cambio temporal

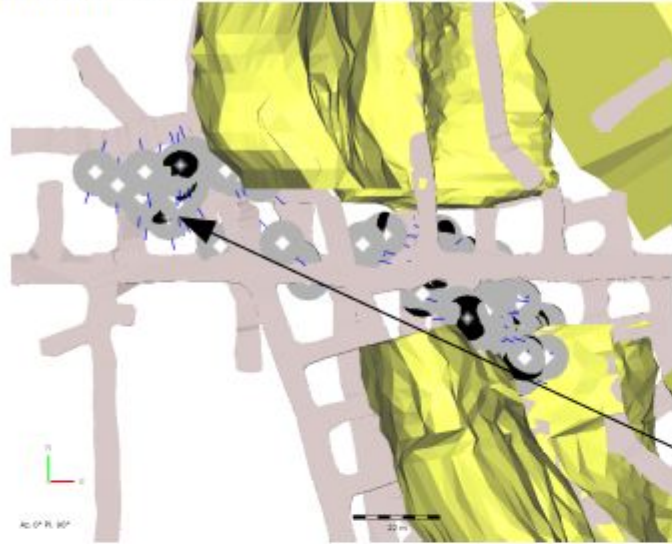
Evento mL1.7



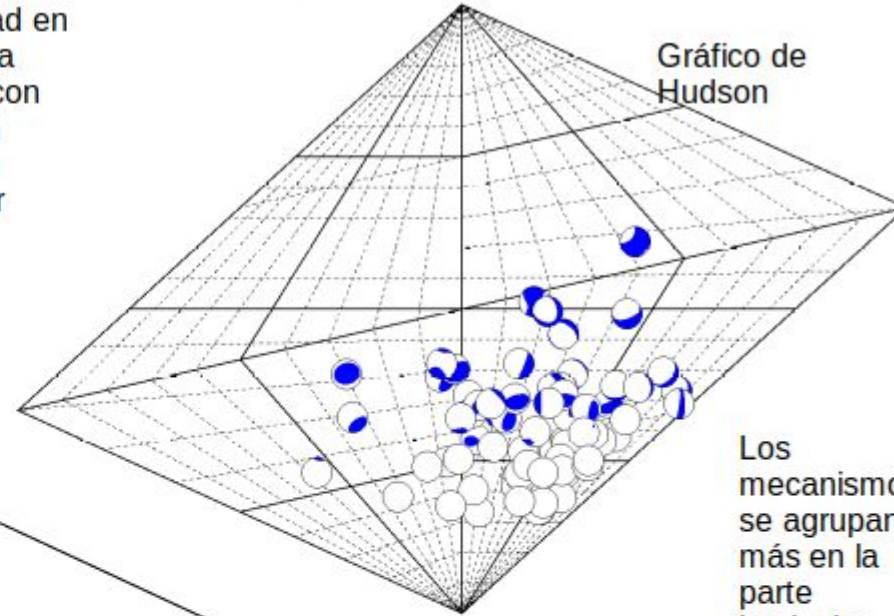
Mecanismos de fuente de los eventos en el pilar 3804 y zonas adyacentes antes del evento mL1.7.



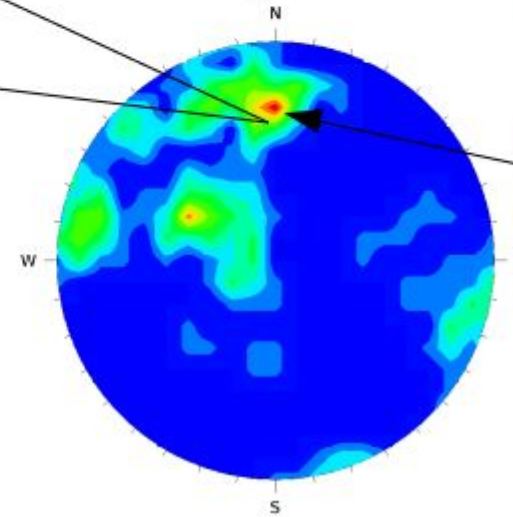
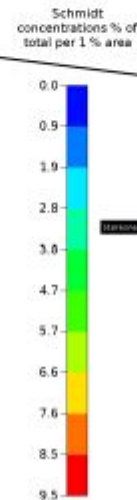
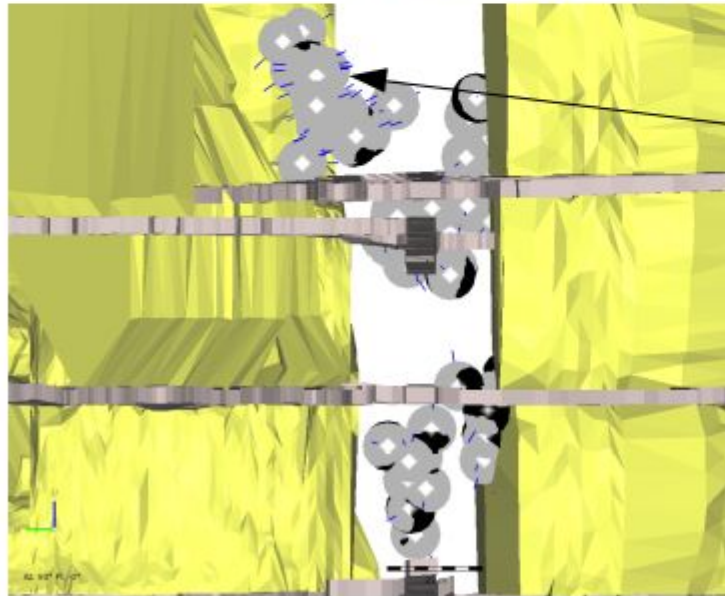
Mecanismos de fuente de los eventos en el pilar 3804 y zonas adyacentes **después** del evento mL1.7.



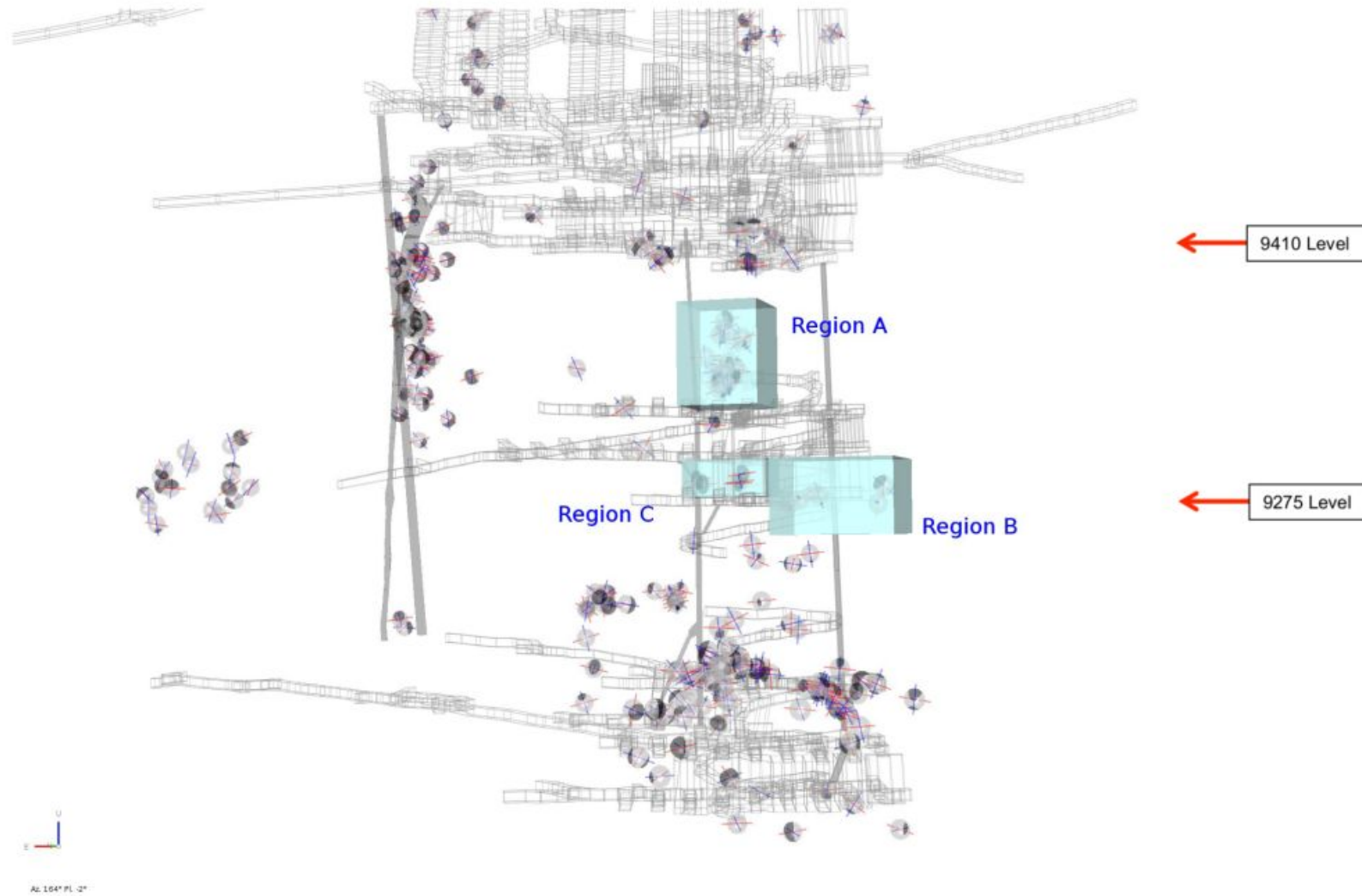
Sismicidad en la esquina Noreste con ejes P en dirección Norte Sur



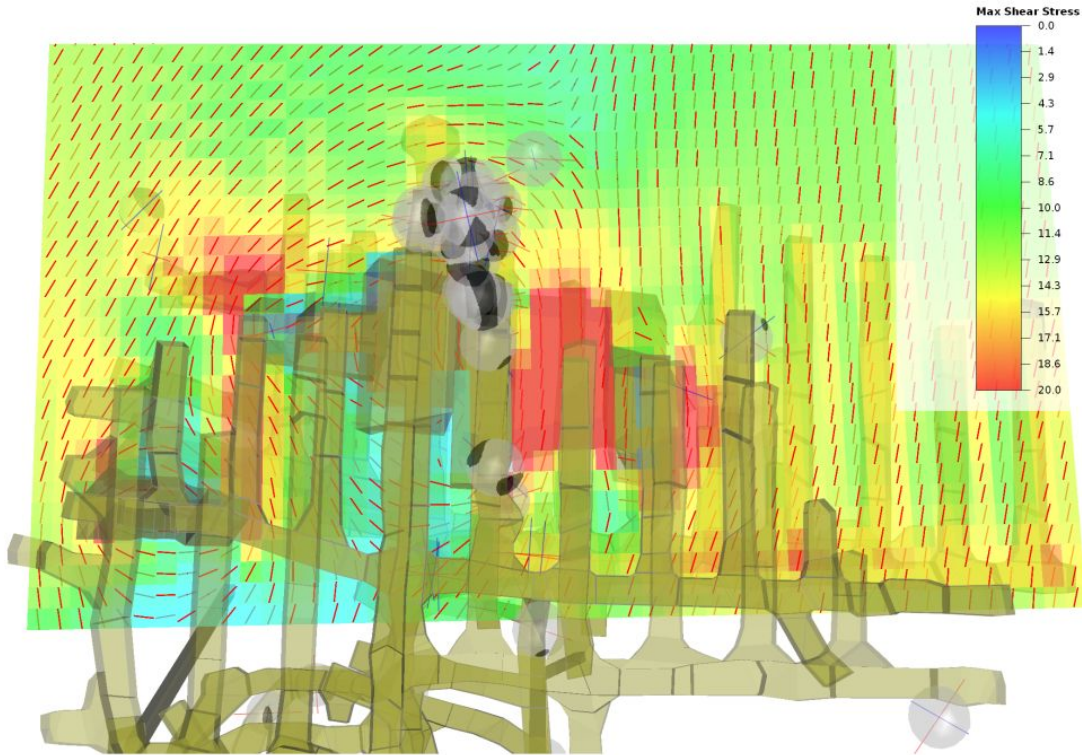
Los mecanismos se agrupan más en la parte implosiva



Ejemplo, mina Williams, Barrick – Hemlo (Earl, 2014)



Modelo original



Original model:

$$\sigma_1 : 358 / 10^\circ$$

$$\sigma_2 : 093 / 28^\circ$$

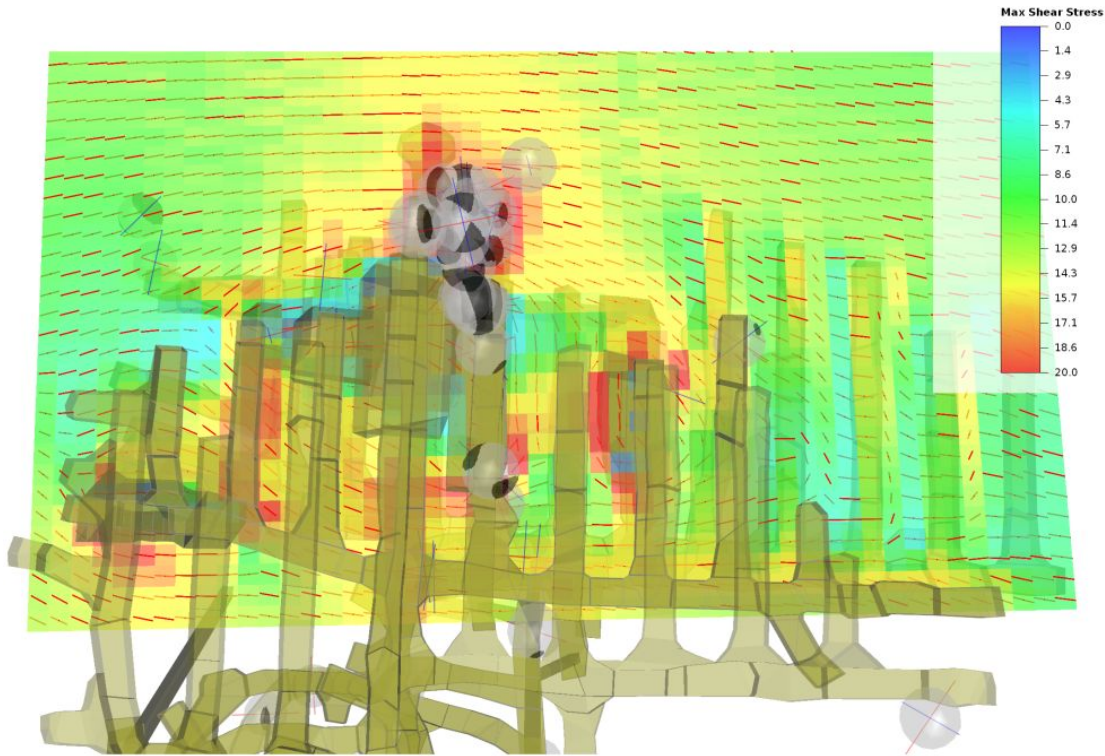
$$\sigma_3 : 250 / 60^\circ$$

(Earl, 2014)

	Model 1: Region A	Model 1: Region B	Model 1: Region C
Seismic P (Proxy- σ_1)			
Model Sigma 1			
Seismic T (Proxy- σ_3)			
Model Sigma 3			



Nuevo modelo



New model (#2):

$$\sigma_1 : 079\% \ 20^\circ$$

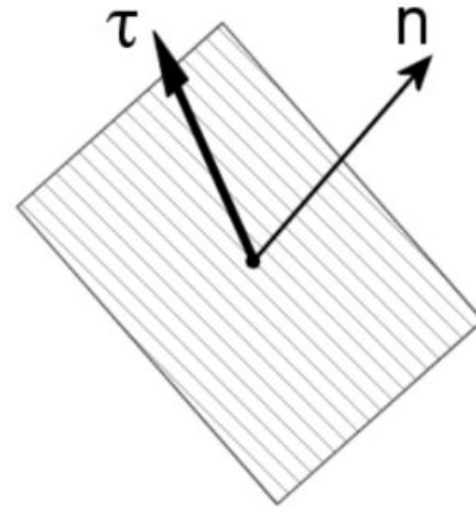
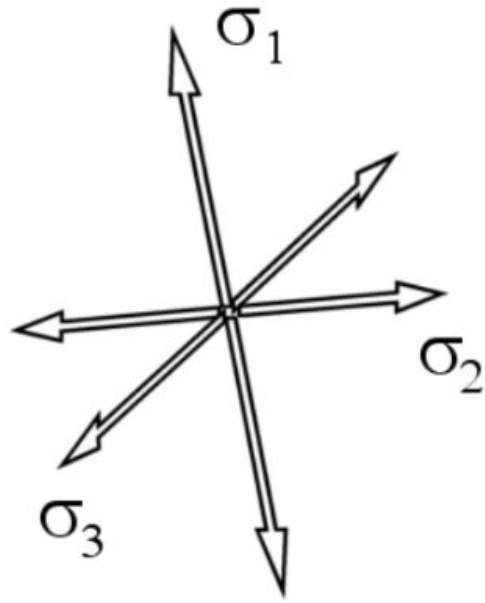
$$\sigma_2 : 195\% \ 30^\circ$$

$$\sigma_3 : 330\% \ 60^\circ$$

(Earl, 2014)

	Model 3: Region A	Model 3: Region B	Model 3: Region C
Seismic P (Proxy-01)			
Model Sigma 1			
Seismic T (Proxy-03)			
Model Sigma 3			

Bott M.H.P. (1959) Mecánica de fallamiento oblicuo. La falla se desliza en la dirección del esfuerzo de corte máximo.



Normal to the plane

$$\mathbf{n} = (n_1, n_2, n_3)$$

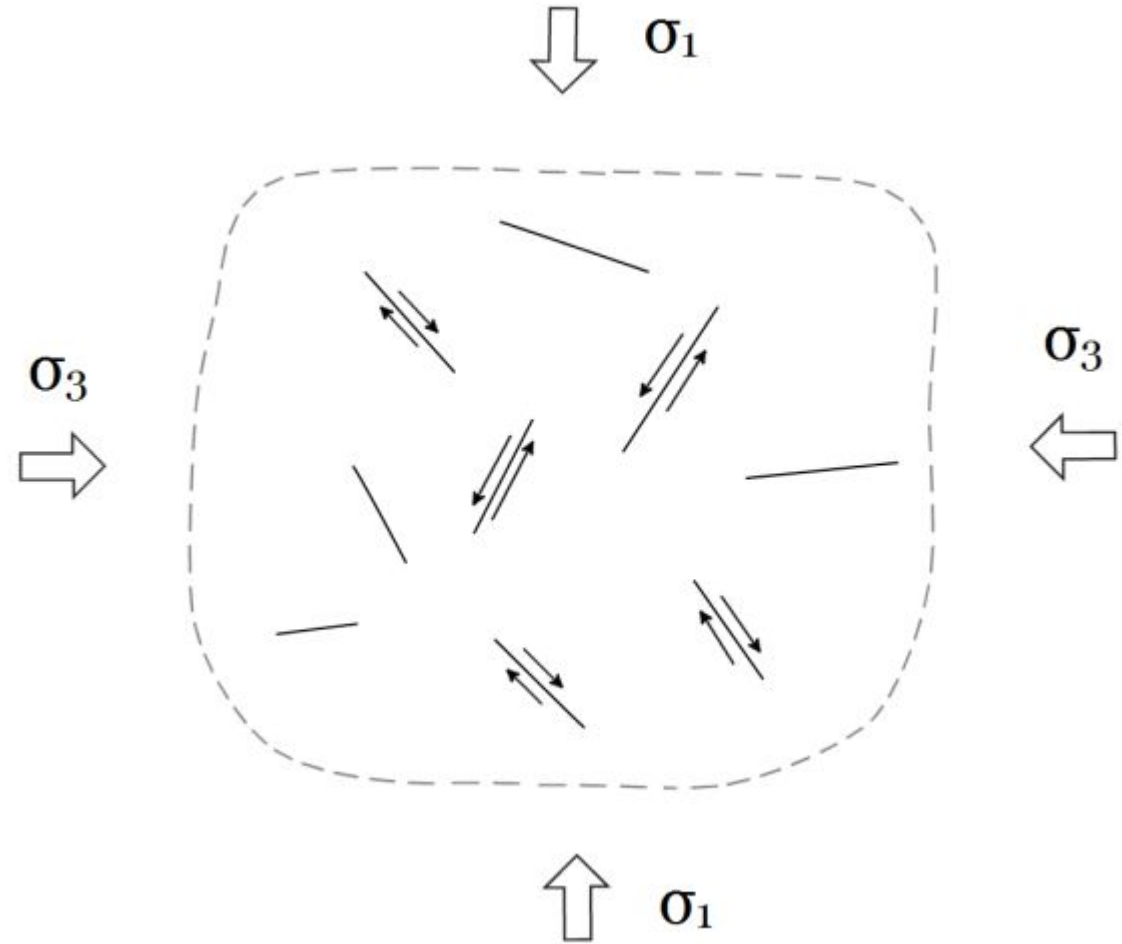
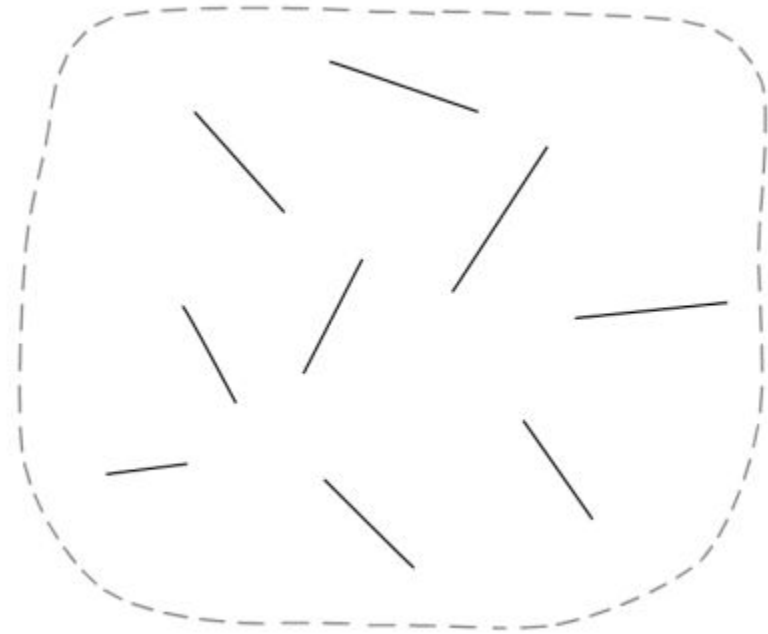
Shear traction

$$\boldsymbol{\tau} = (\tau_1, \tau_2, \tau_3)$$

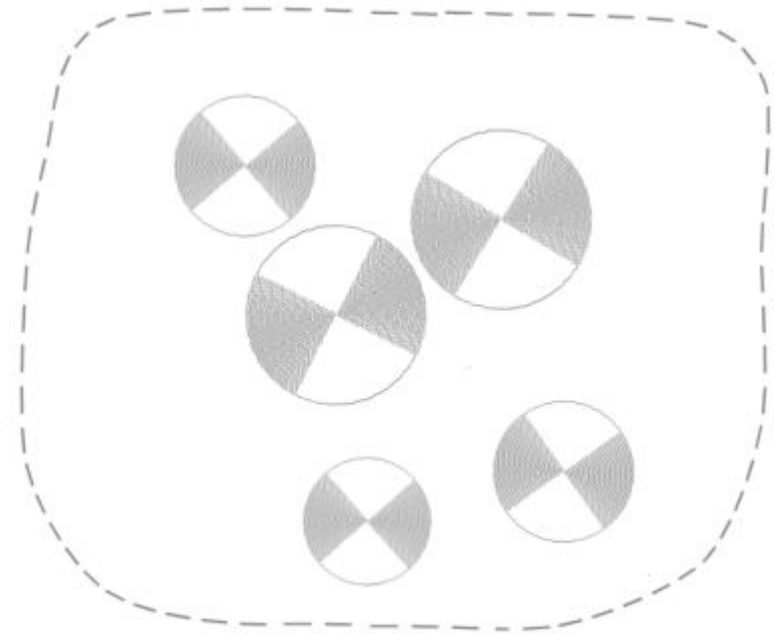
$$\boldsymbol{\tau} = (\sigma_1 - \sigma_3) \begin{bmatrix} n_1(n_3^2 + n_2^2 R) \\ n_2(n_3^2 + n_2^2 R - R) \\ n_3(n_3^2 + n_2^2 R - 1) \end{bmatrix}, \text{ where } R = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3}$$



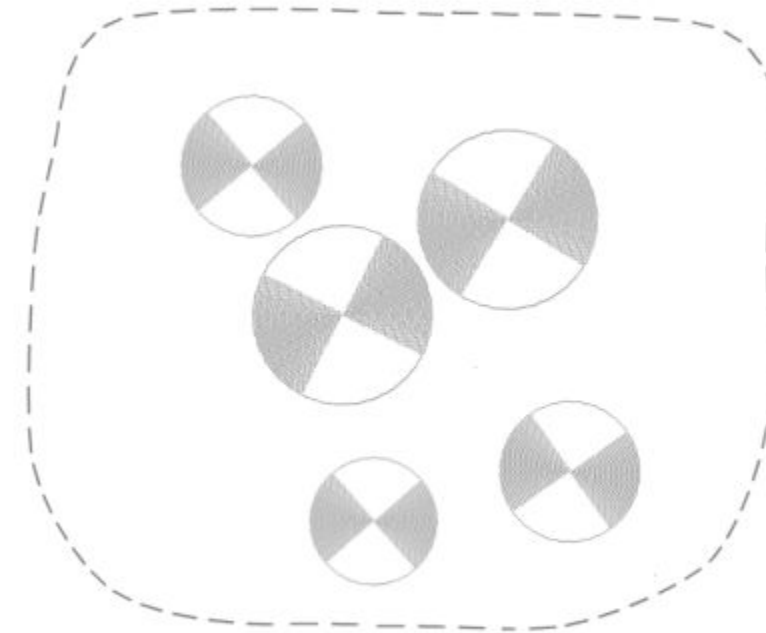
Inversión de esfuerzos



Inversión de esfuerzos



σ_3
→



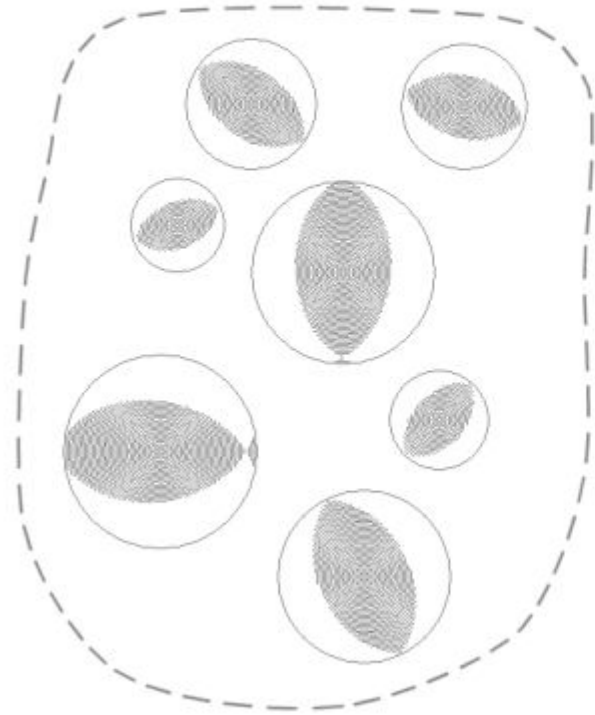
↑ σ_1

σ_3
←

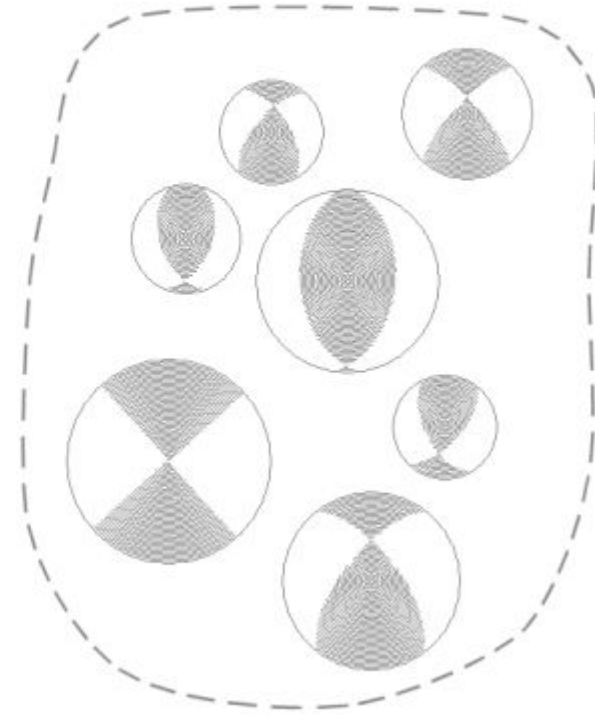


Inversión de esfuerzos

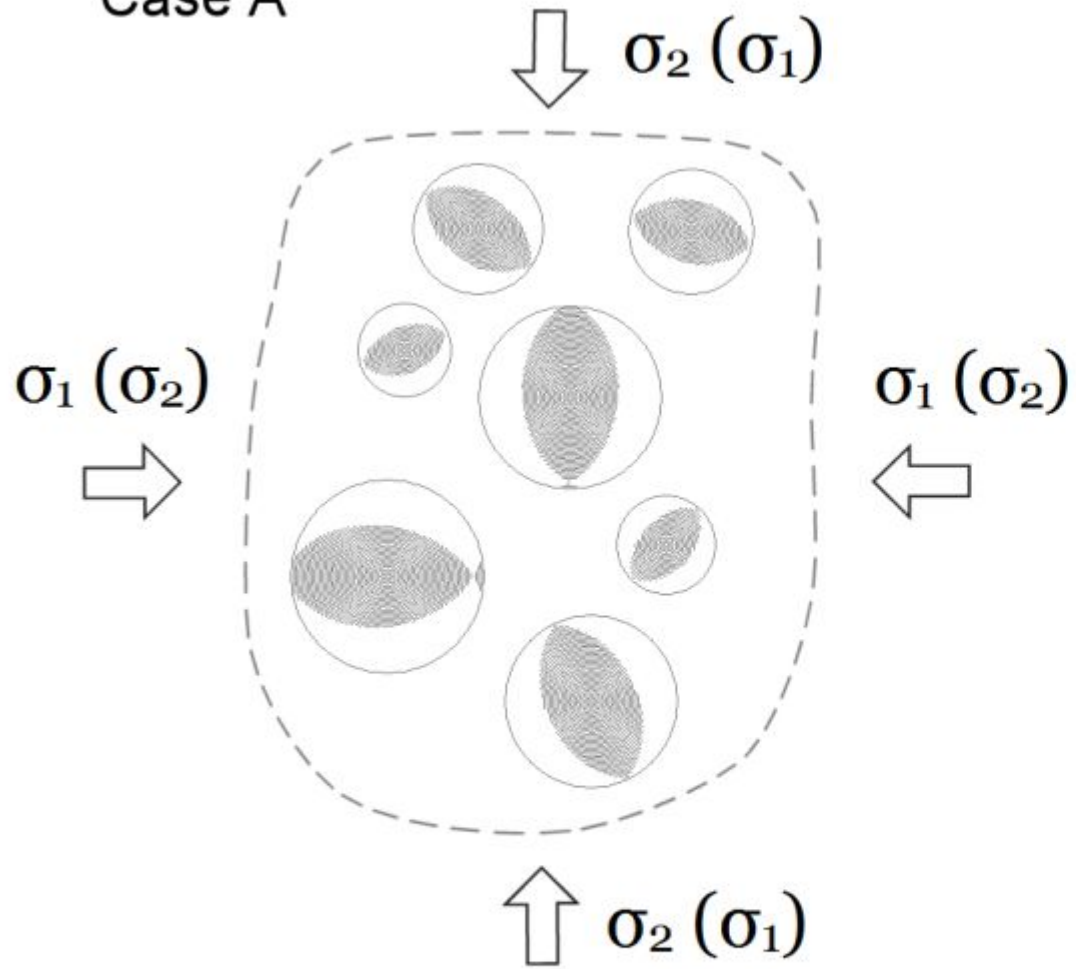
Case A



Case B



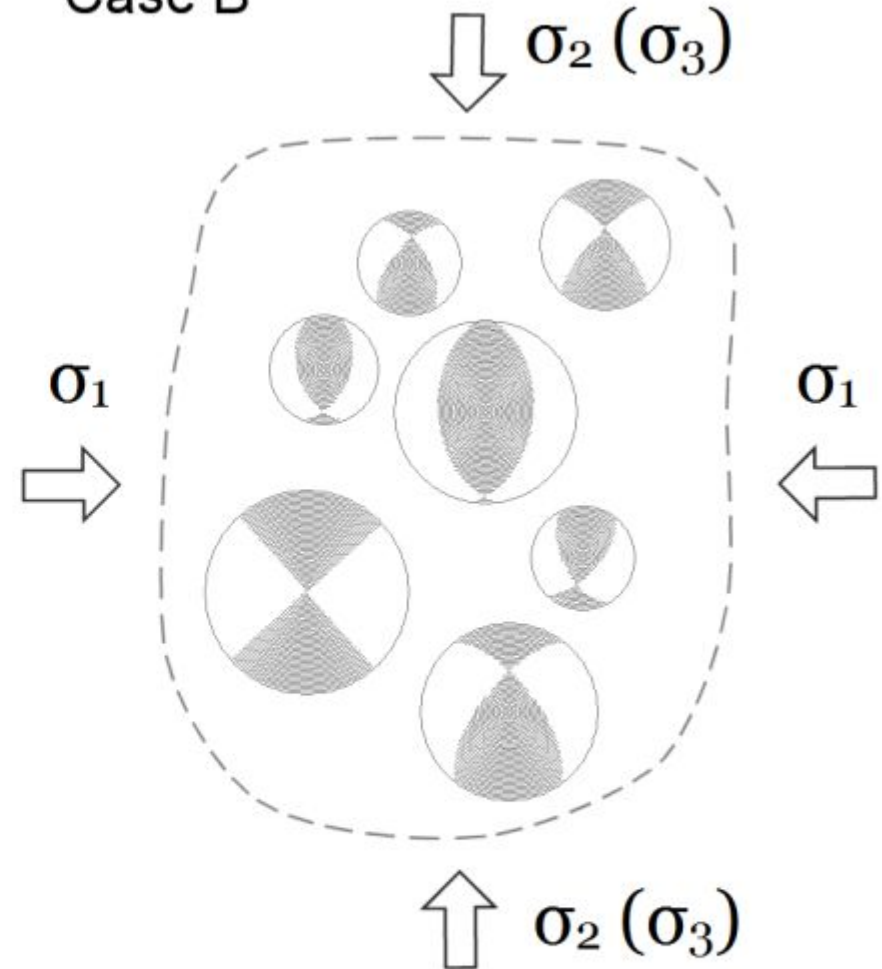
Case A



$$|\sigma_1| \approx |\sigma_2|$$

$$R = (|\sigma_1| - |\sigma_2|) / (|\sigma_1| - |\sigma_3|) \approx 0$$

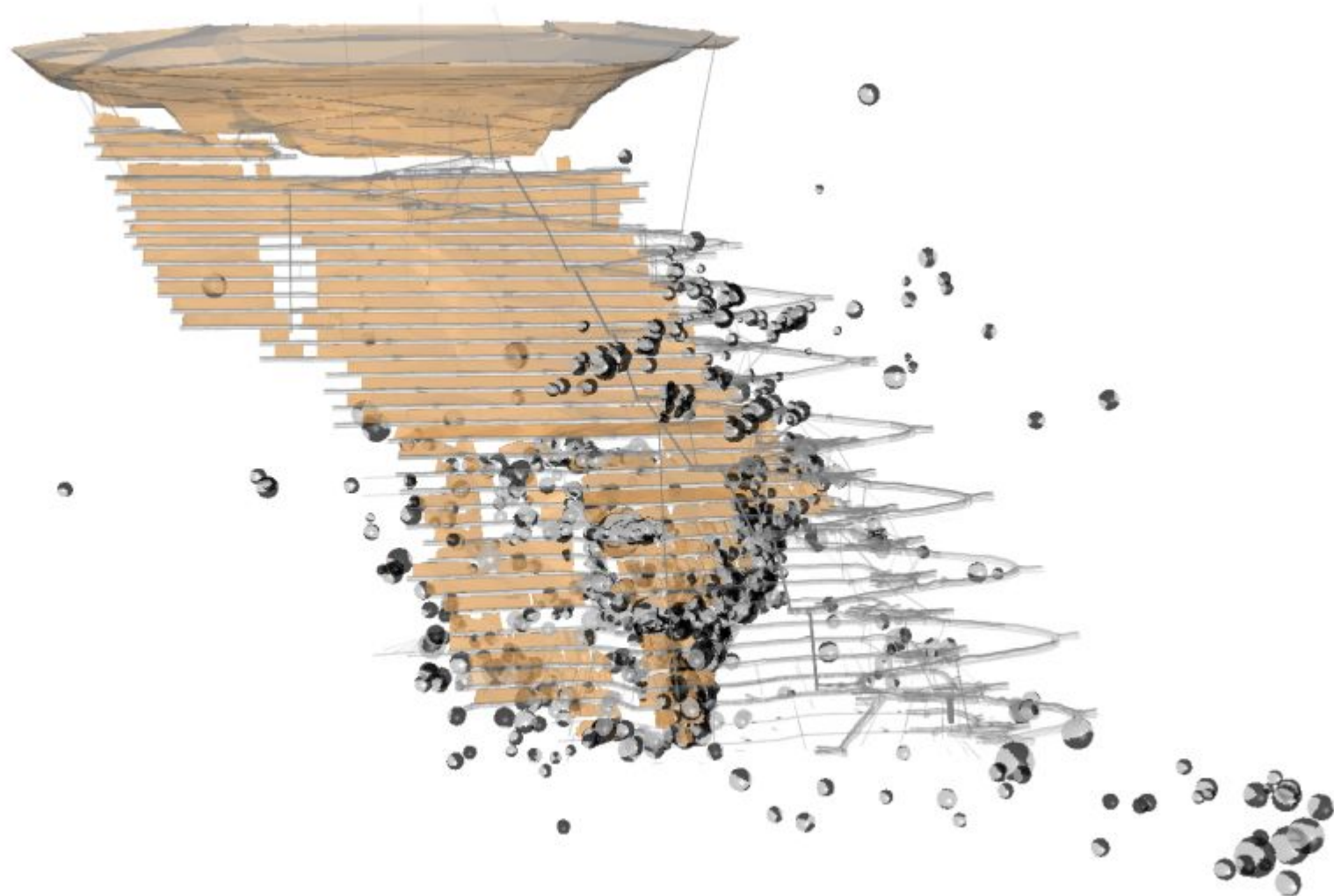
Case B



$$|\sigma_2| \approx |\sigma_3|$$

$$R = (|\sigma_1| - |\sigma_2|) / (|\sigma_1| - |\sigma_3|) \approx 1$$





Az. 97° Pl. 5°



Date: Time: 10:34:08 Magnitude: -1.5

Full Moment Tensor (SWD coordinate system)

M =	-0.59	0.53	-0.39	$2.8 \cdot 10^7$ N·m
	0.53	0.76	-0.22	
	-0.39	-0.22	0.34	



TOTAL = 0.14 ISO + 0.86 DEV

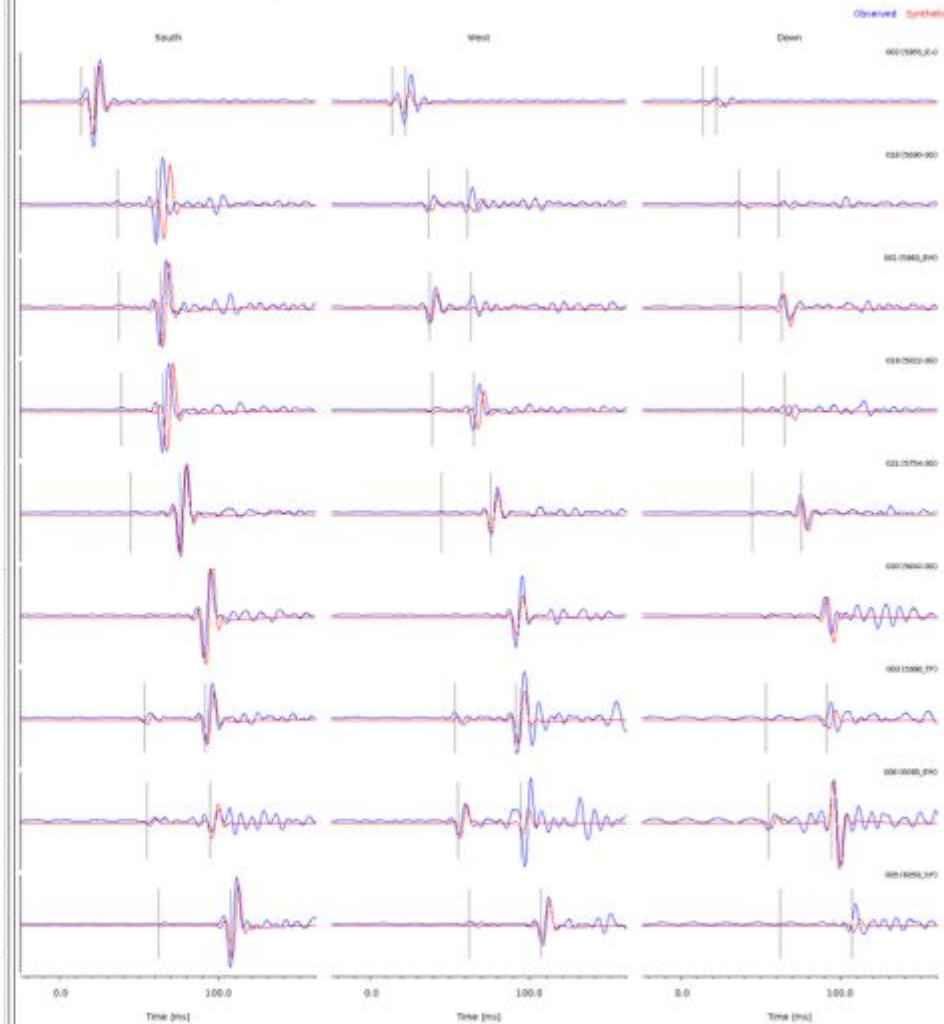
Nodal Planes

#	Strike [deg]	Dip [deg]	Rake [deg]
1	207	61	8
2	114	83	151

Principal Axes

	Azimuth [deg]	Plunge [deg]
T	67	25
P	164	15
B	281	60

Waveforms of velocity



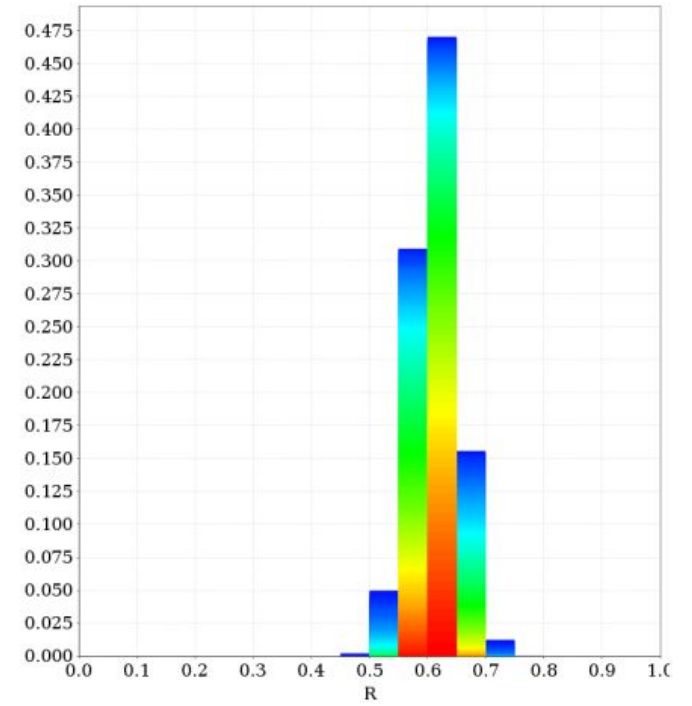
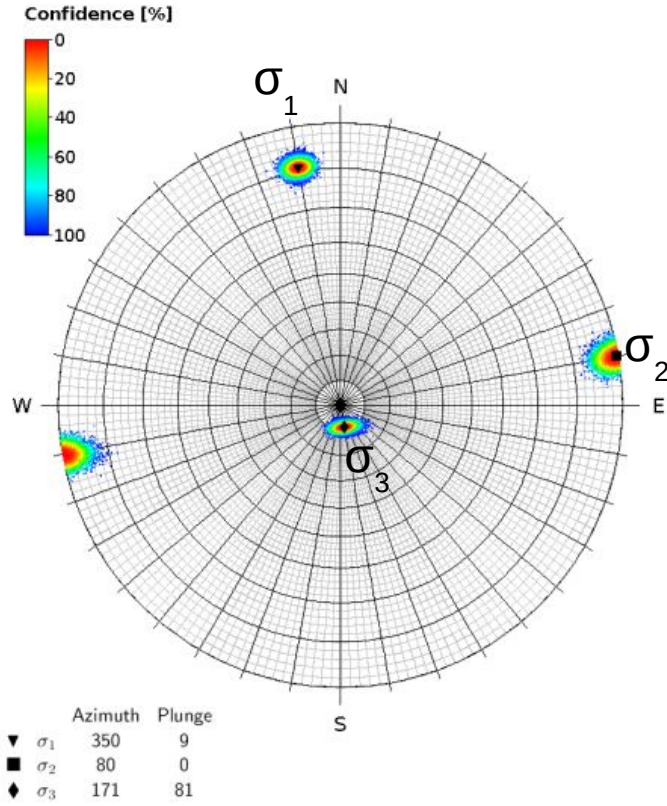
Filter: Butterworth, order 4, low pass 150.0 Hz



Ejemplo:

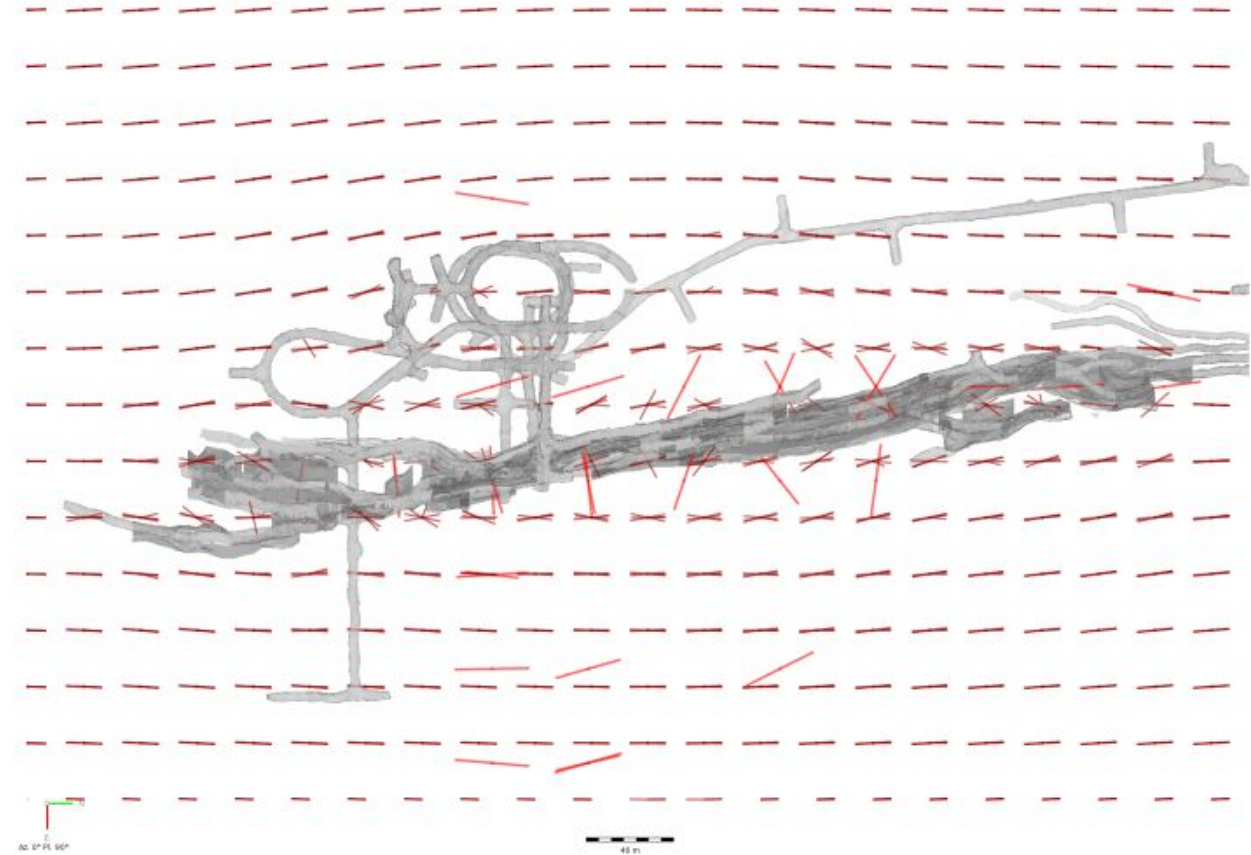
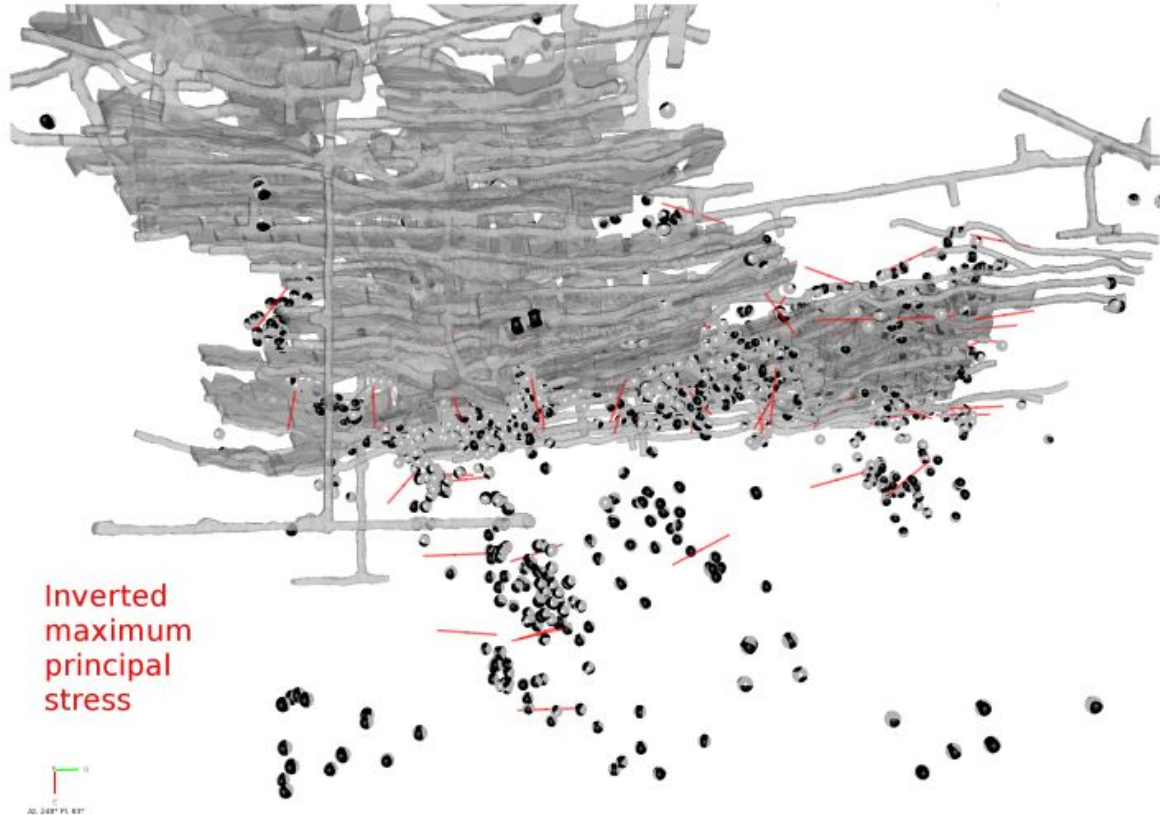


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U
Az. 224° Pl. 64°



$R = (\sigma_1 - \sigma_2) / (\sigma_1 - \sigma_3) = 0.61$

Ejemplo:





Parte 2: Comprensión de la mecánica de estallidos de roca

Scenario A:

Slip along a structure in the footwall. Dynamic loading to the drives by stress waves. Damage of drives is expected to be more in a form of seismic shakedown, less as a bulking of stress-fractured ground.

Engineering Demand Parameter (EDP): peak ground velocity (PGV or PPV) or peak dynamic stress, cumulative absolute displacement (CAD)

Damage:

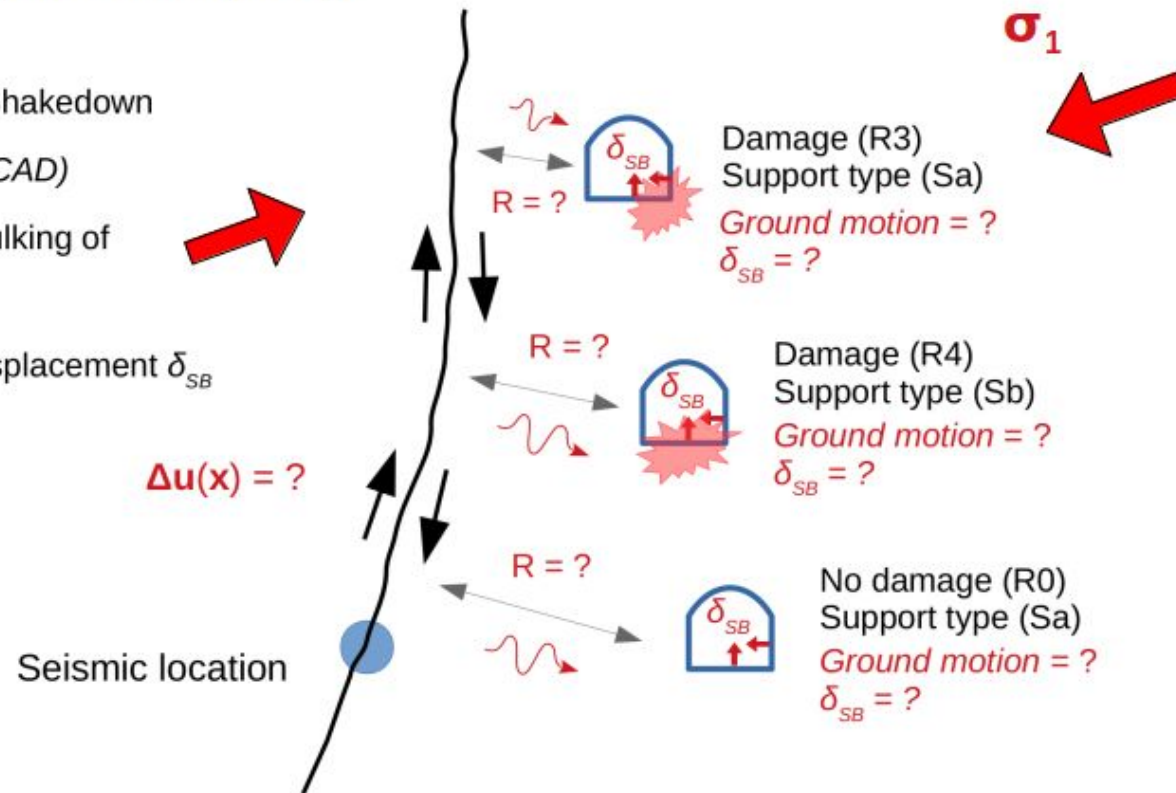
Variant 1 (more widespread): Shakedown

EDP = Ground motion (PGV, CAD)

Variant 2 (less widespread): Bulking of stress-fractured ground

EDP = Excavation Surface Displacement δ_{SB}

Note that dynamic loading needs to be assessed using the rupture time history $\Delta u(x, t)$ and distance to the rupture R , not magnitude and distance from source initiation



Scenario B:

Cascading failure in the floor and bottom corners of drives driven by compressional stress oriented sub-orthogonal to the lens. Damage of drives is expected to be more in a form of bulking of stress-fractured ground and less as a seismic shakedown.

Engineering Demand Parameter (EDP): magnitude and rate of tangential straining in the floor of drives, excavation surface displacement (δ_{SB}).

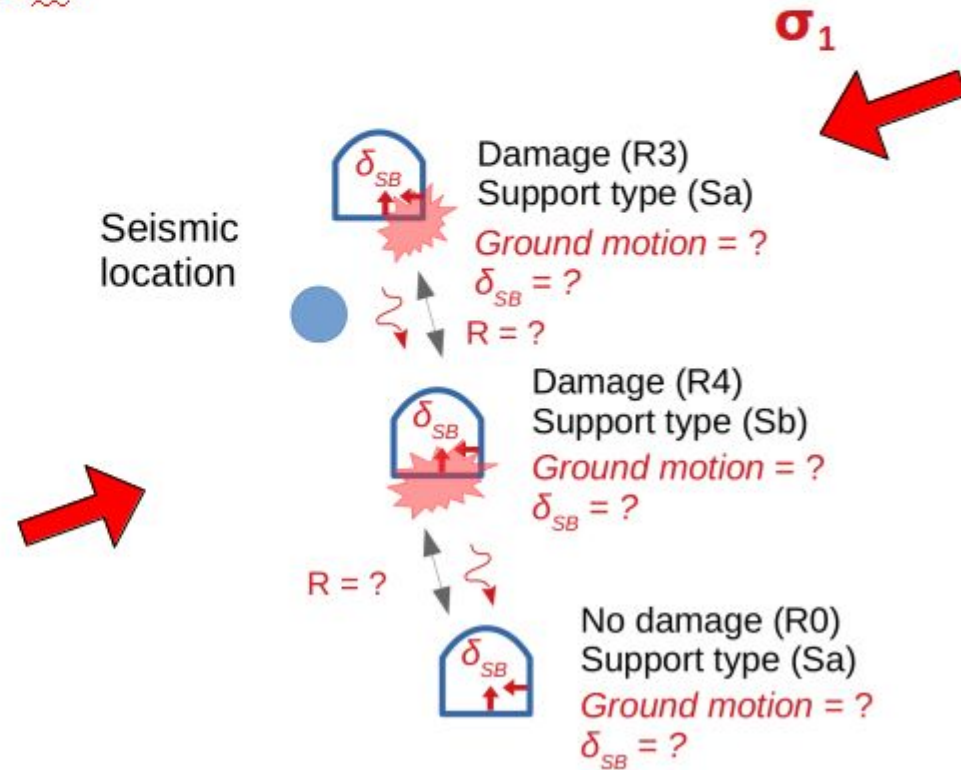
Damage:

Variant 1 (more widespread): Bulking of stress-fractured ground

EDP = Excavation Surface Displacement δ_{SB}

Variant 2 (less widespread): Shakedown

EDP = Ground motion (PGV, CAD)





El hipocentro y la localización del daño pueden no coincidir

Damage

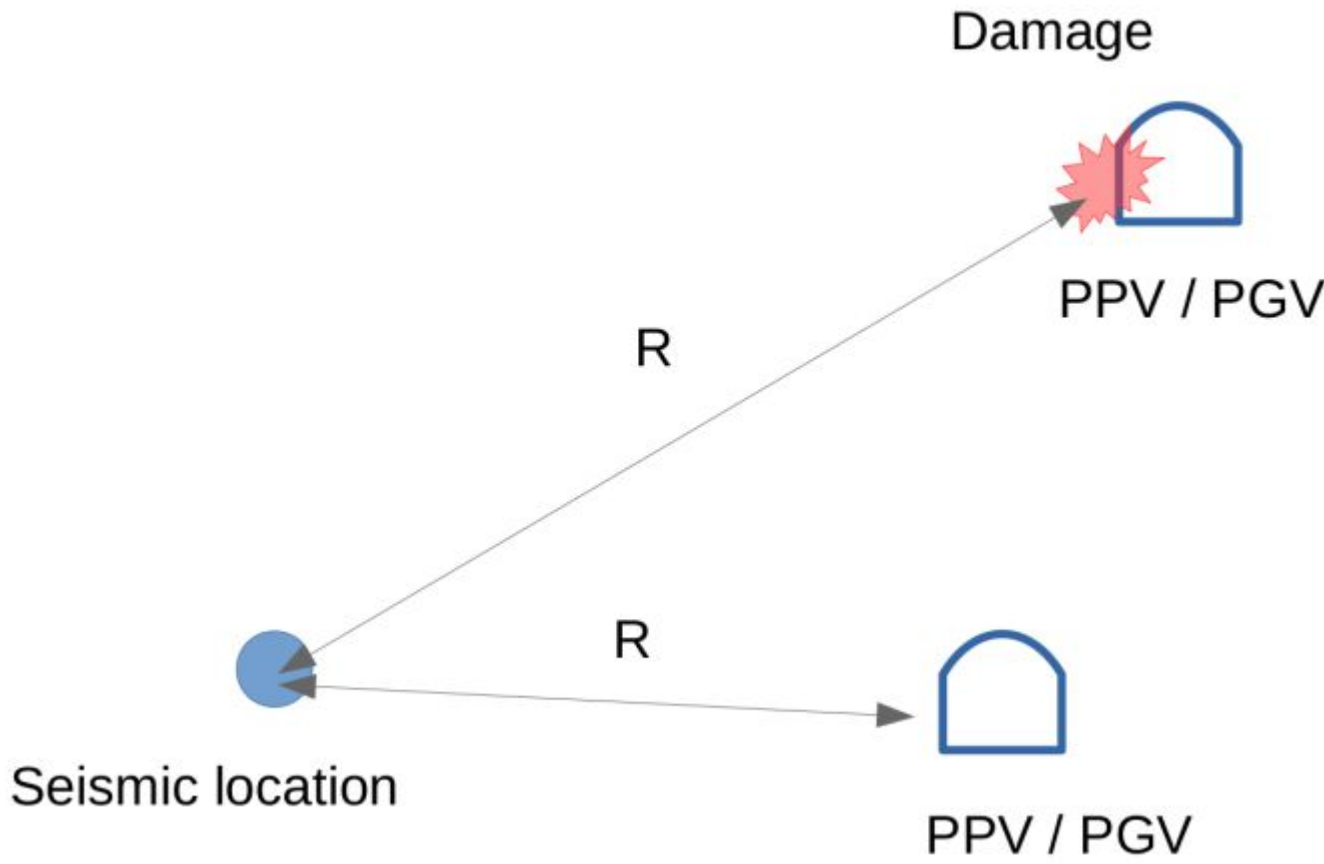


Seismic location

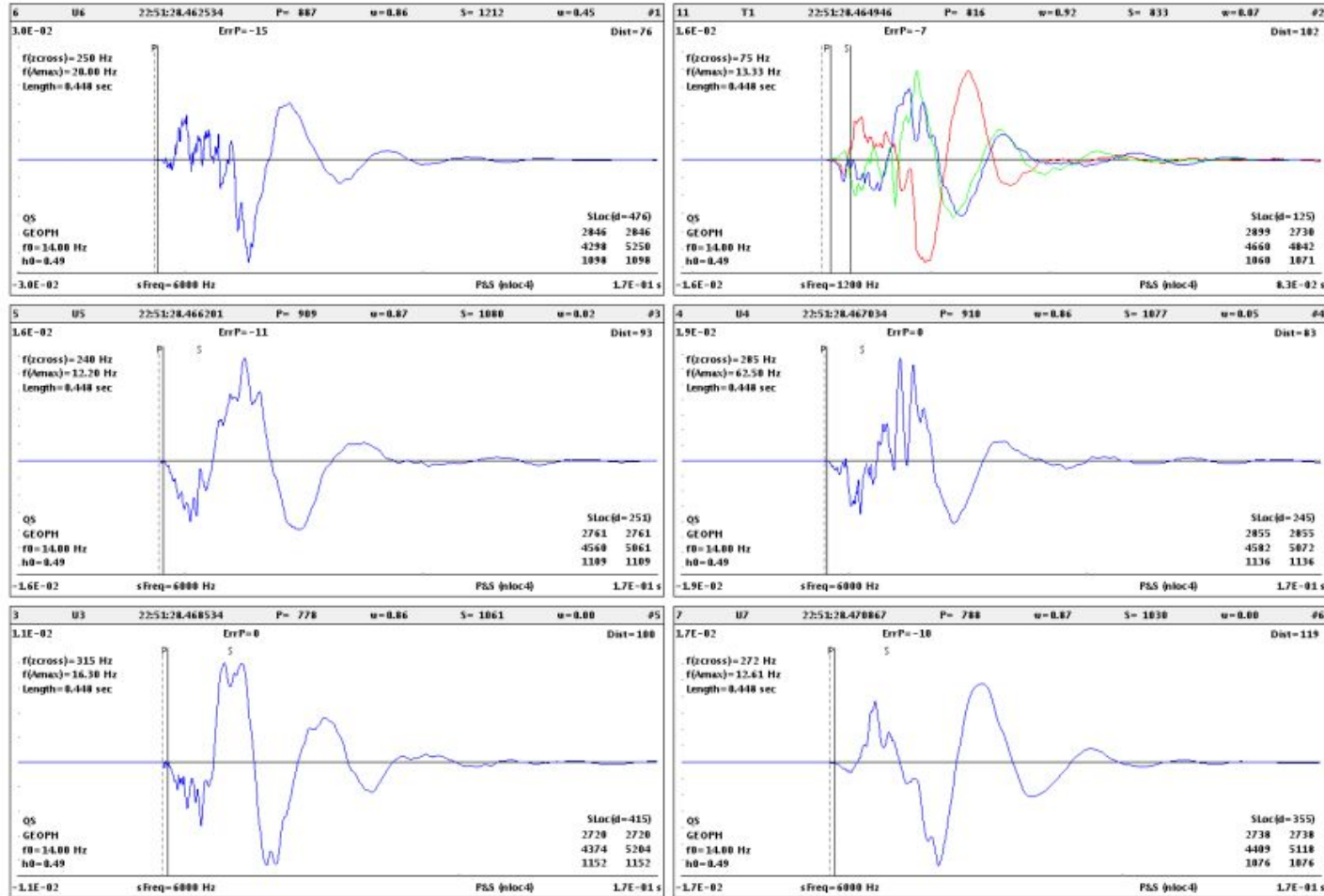




Los cálculos de la carga dinámica a las excavaciones asumiendo fuentes puntuales pueden resultar en aparentes contradicciones

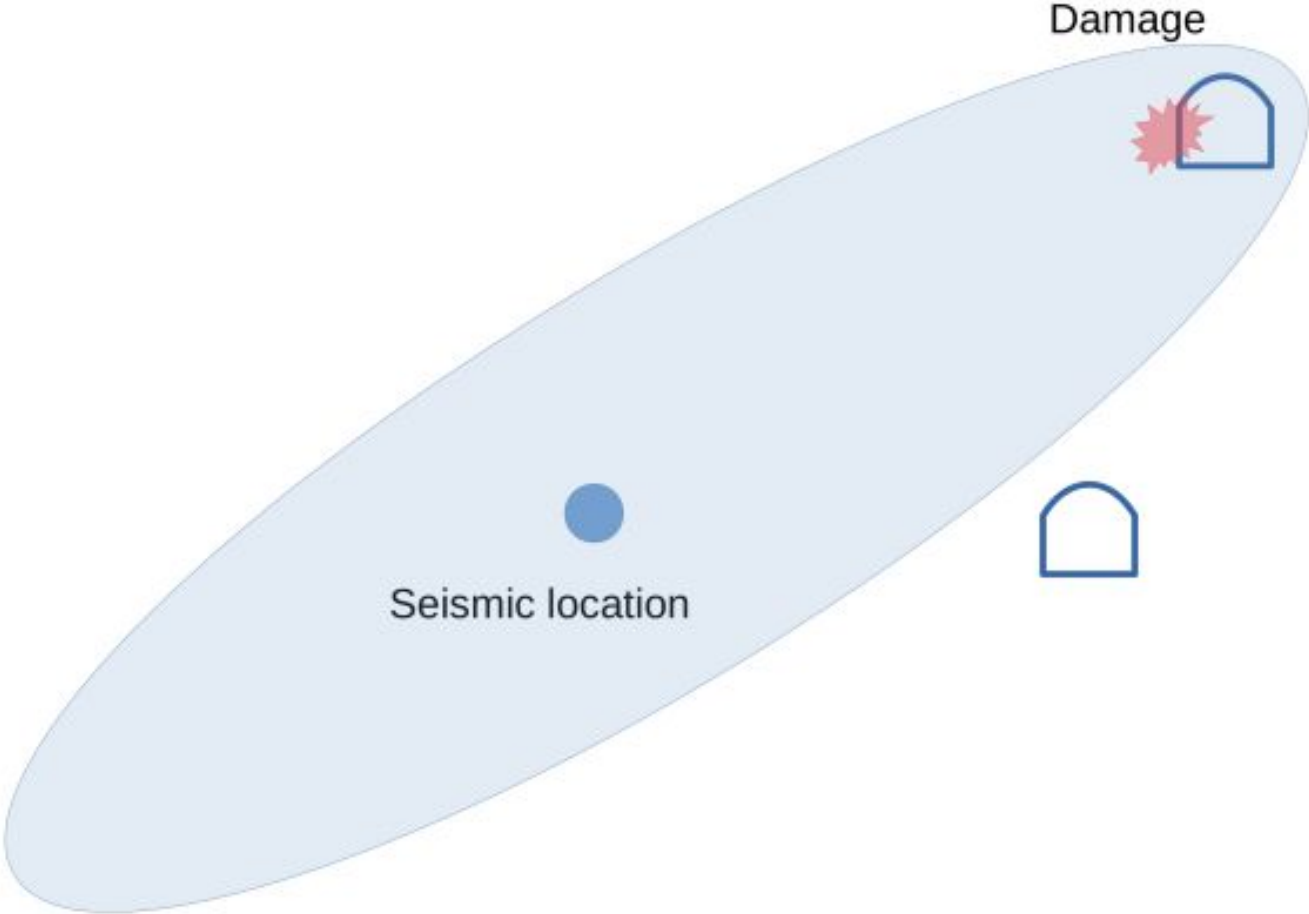


Puede haber incertidumbre en la localización de la fuente

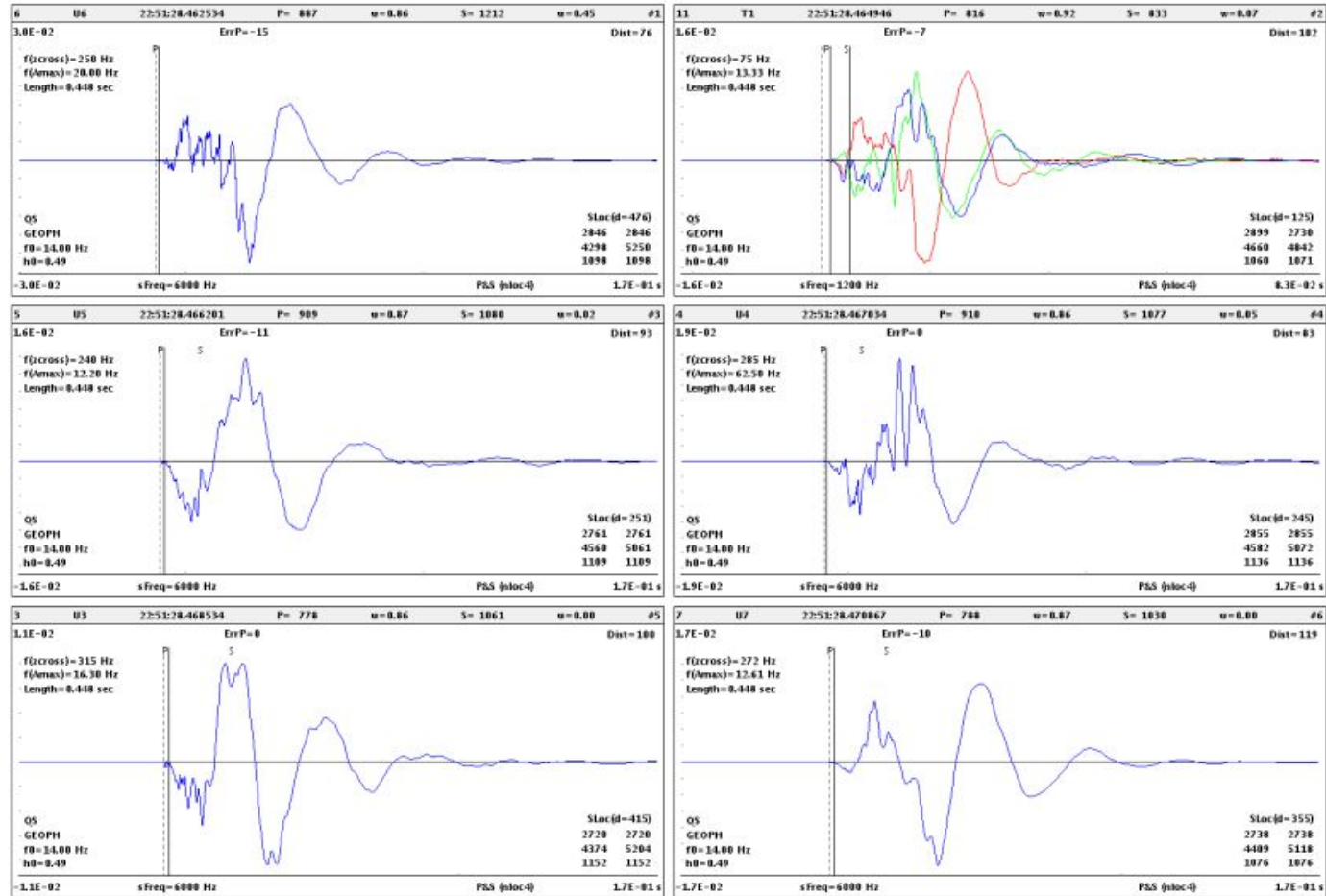




Puede haber incertidumbre en la localización de la fuente



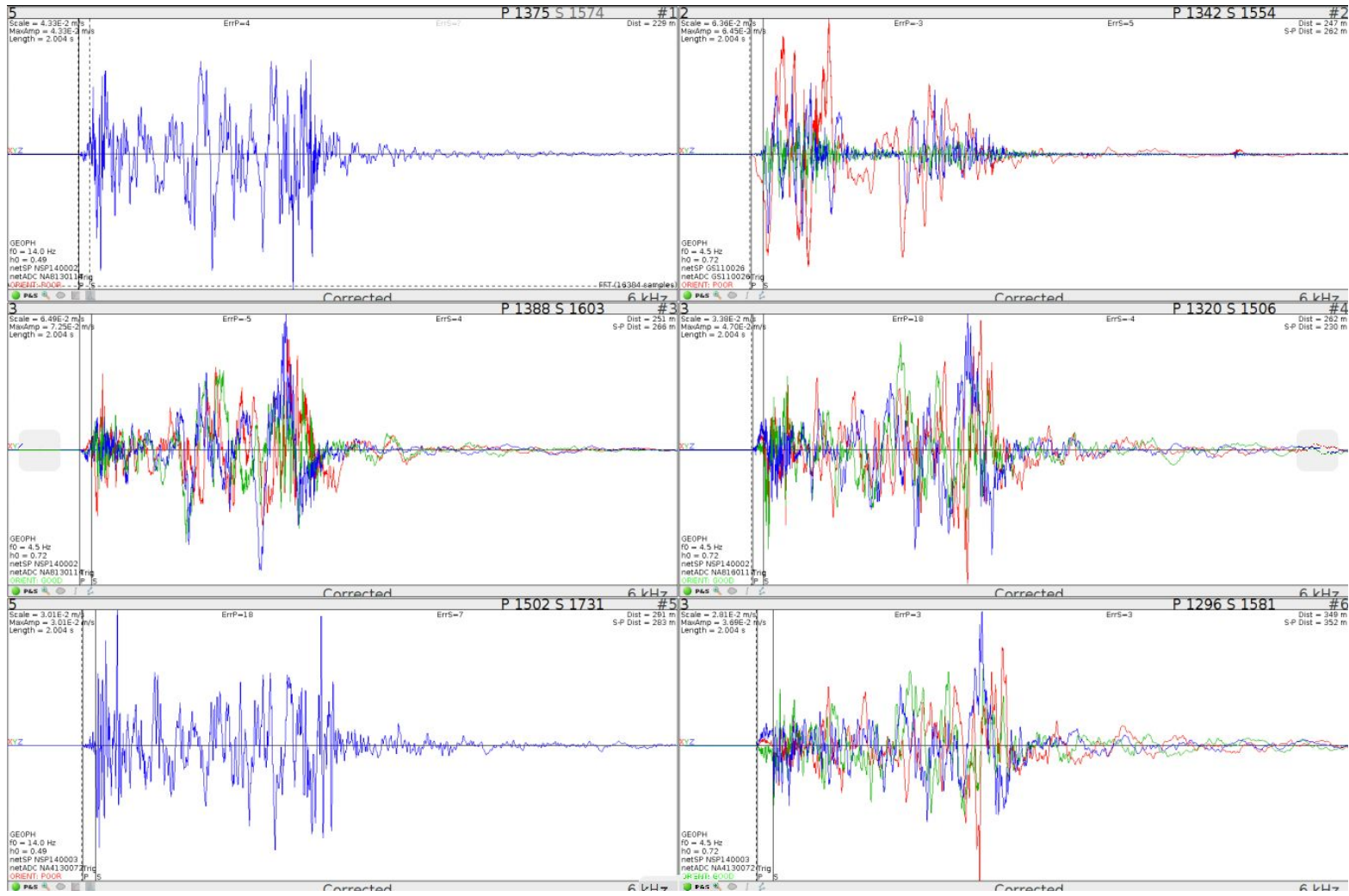
... O las señales más fuertes posteriores pueden haber sido originadas en otros lugares



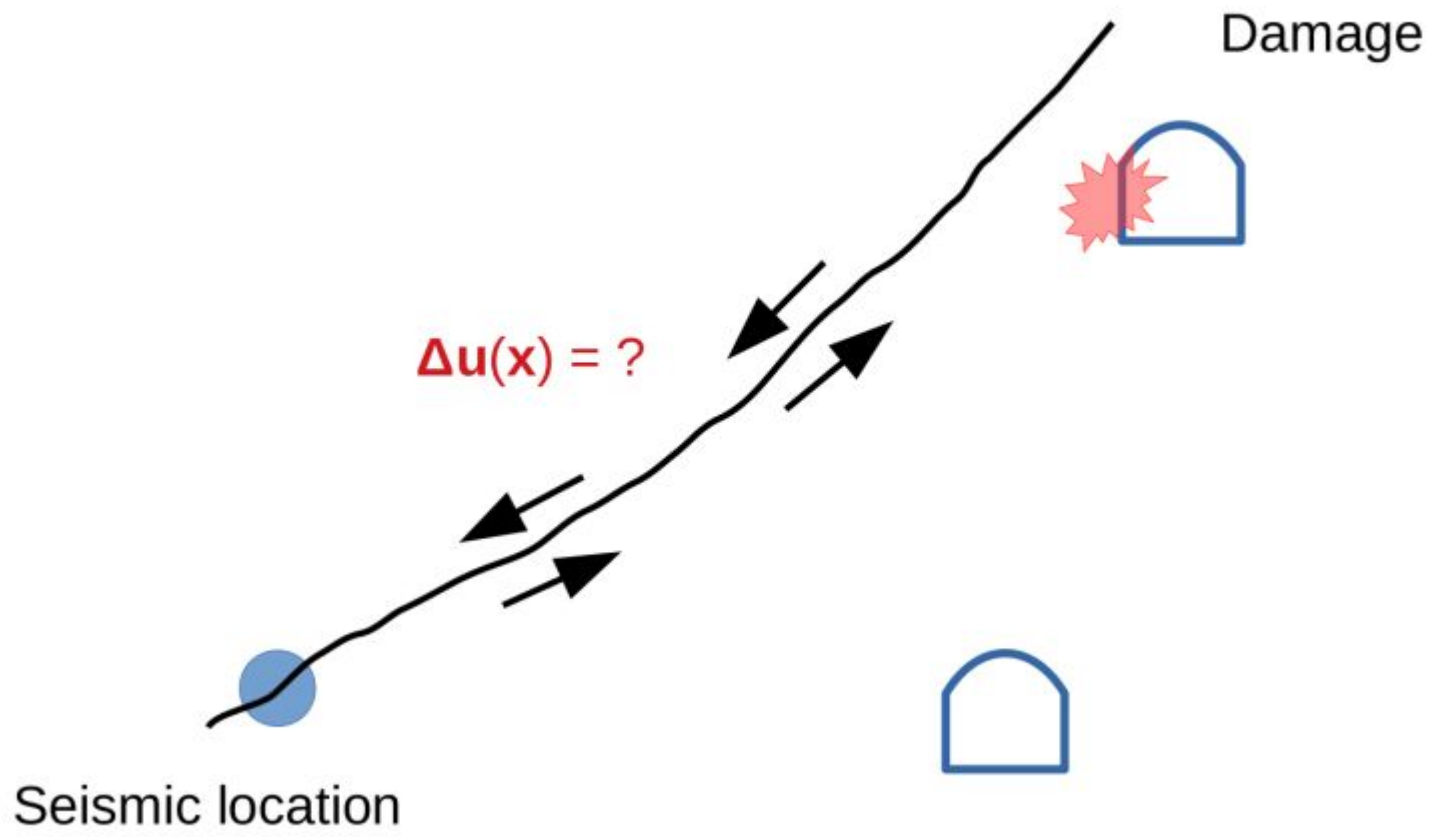
Ejemplo de evento complejo



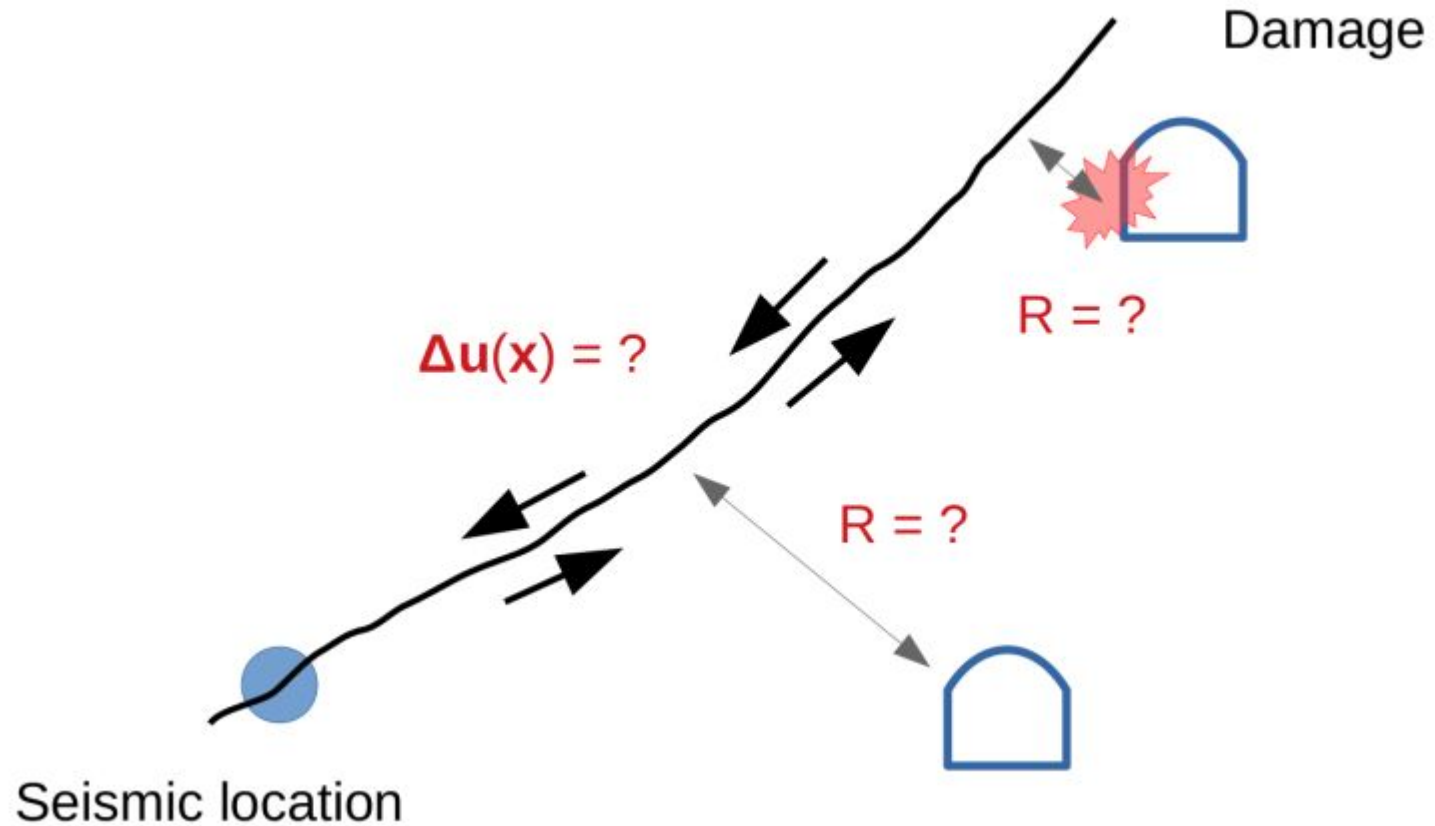
Ejemplo de evento complejo



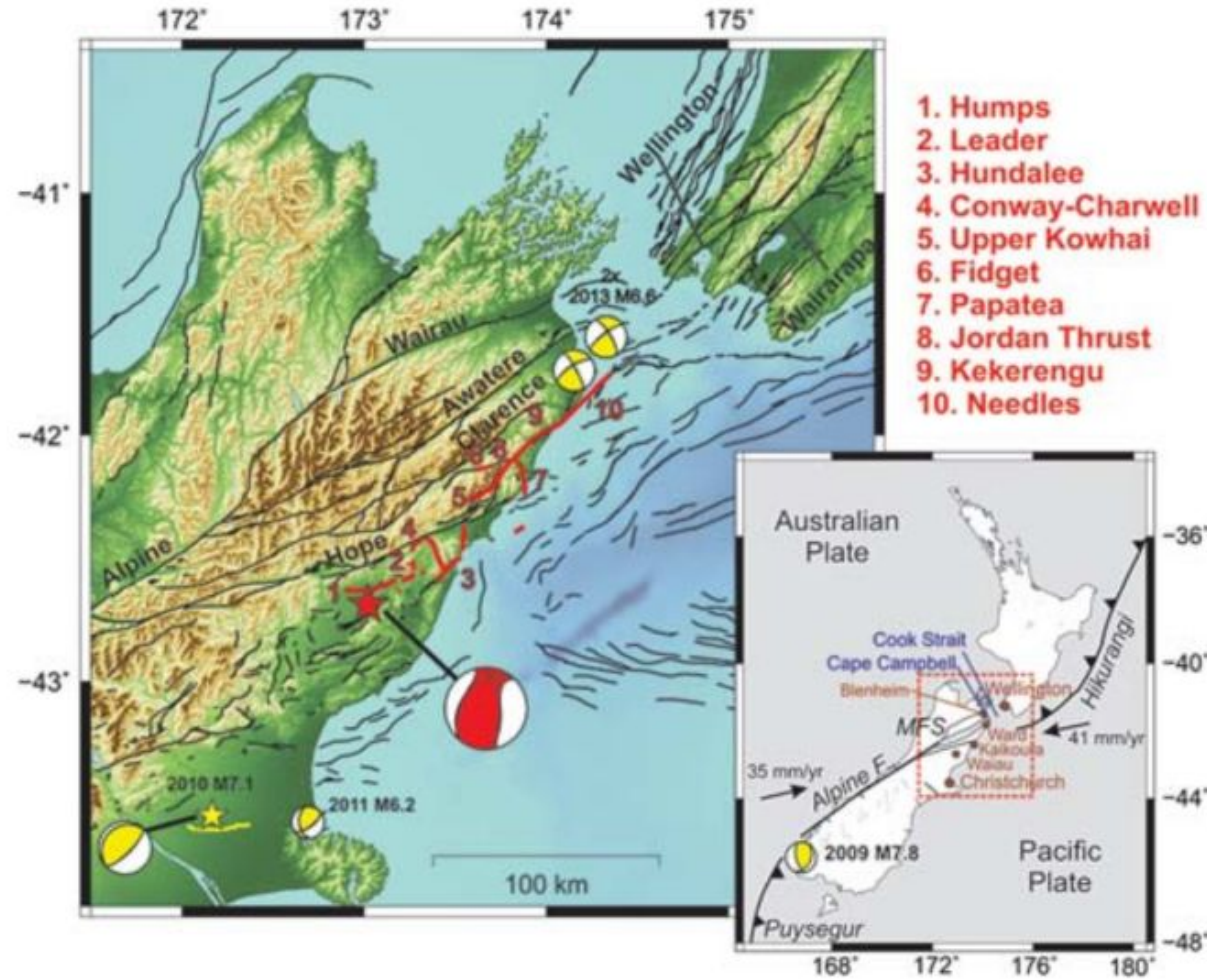
Es importante entender la distribución espacial del deslizamiento en la fuente



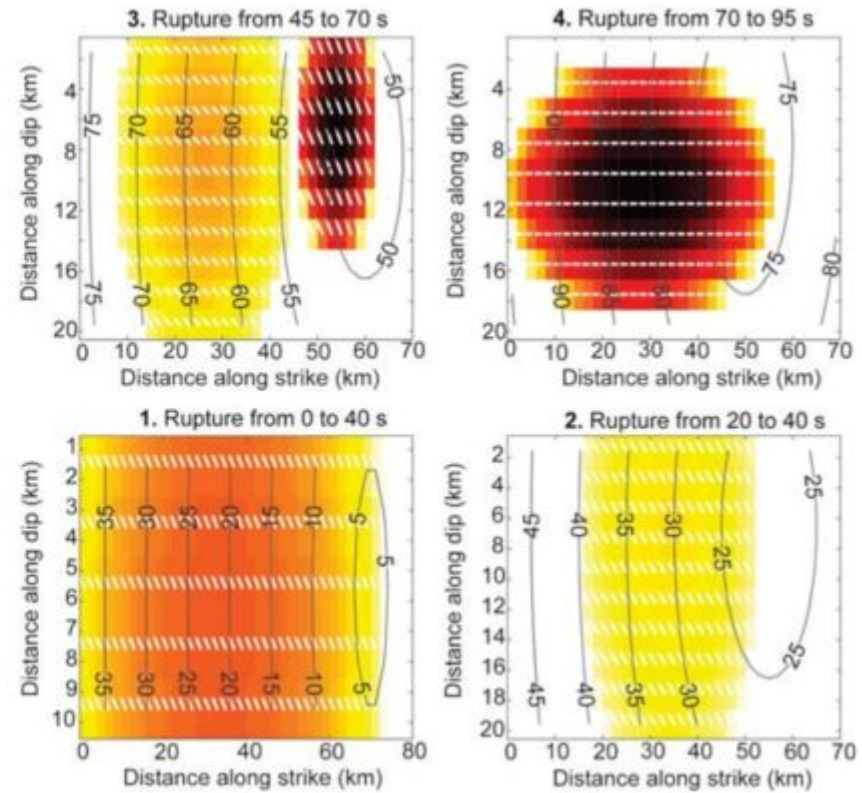
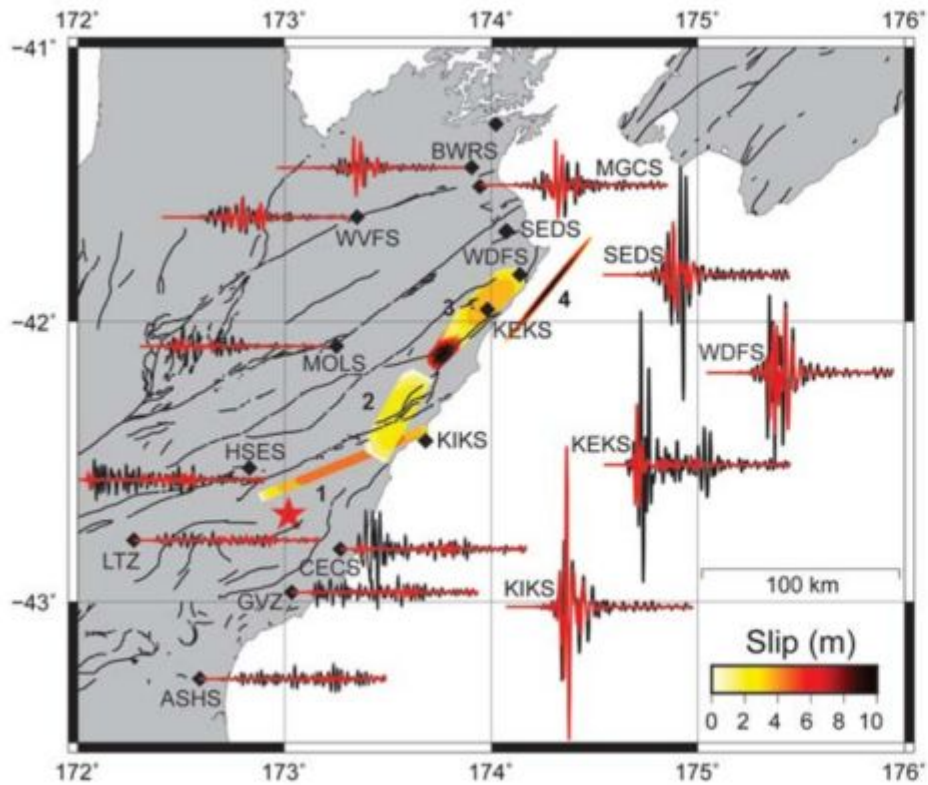
Los cálculos deben hacerse no en relación a la distancia al hipocentro sino usando la distancia a la fuente finita.



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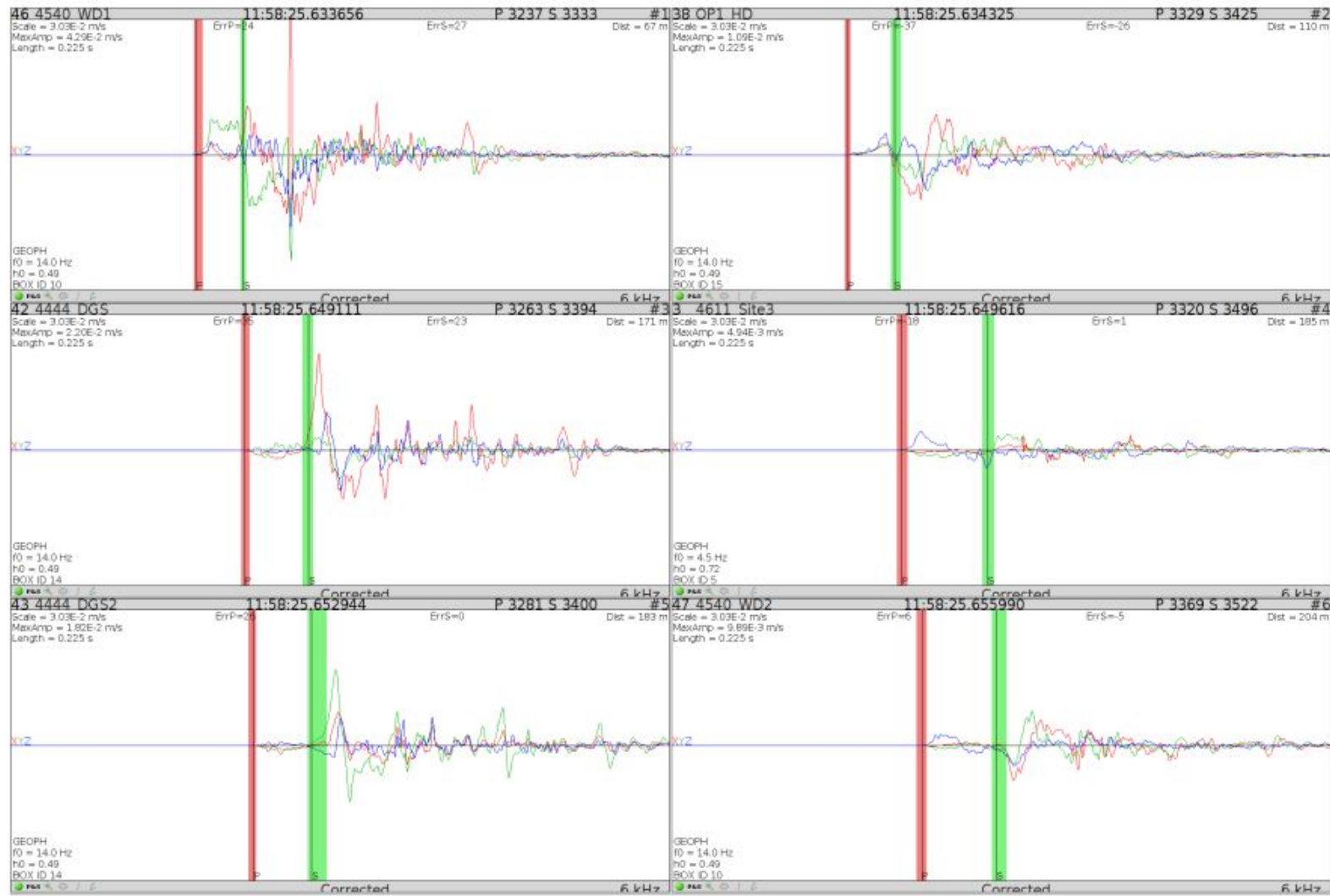


(Kaiser *et al.*, 2017)

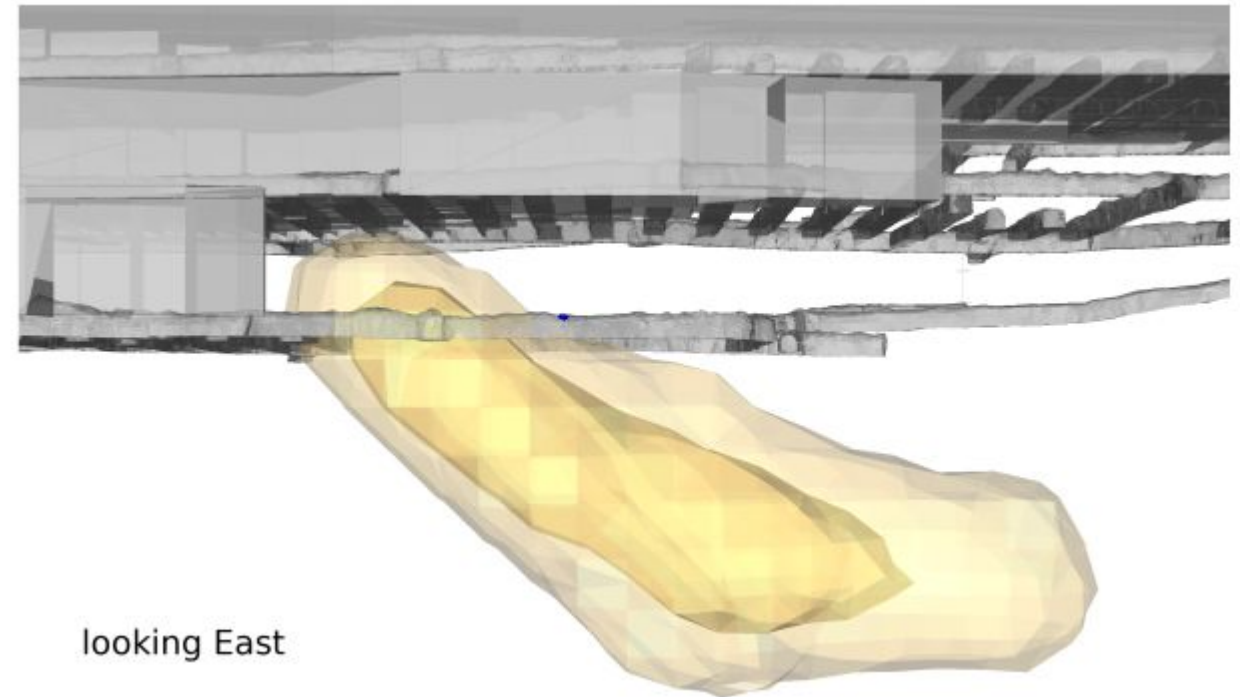
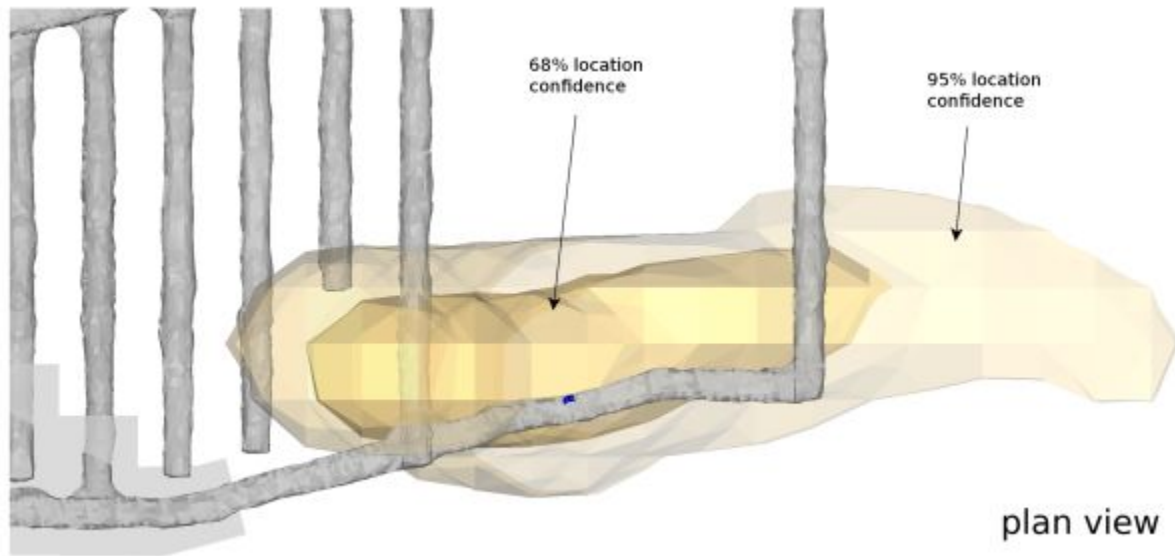


(Kaiser *et al.*, 2017)

Caso de estudio A:



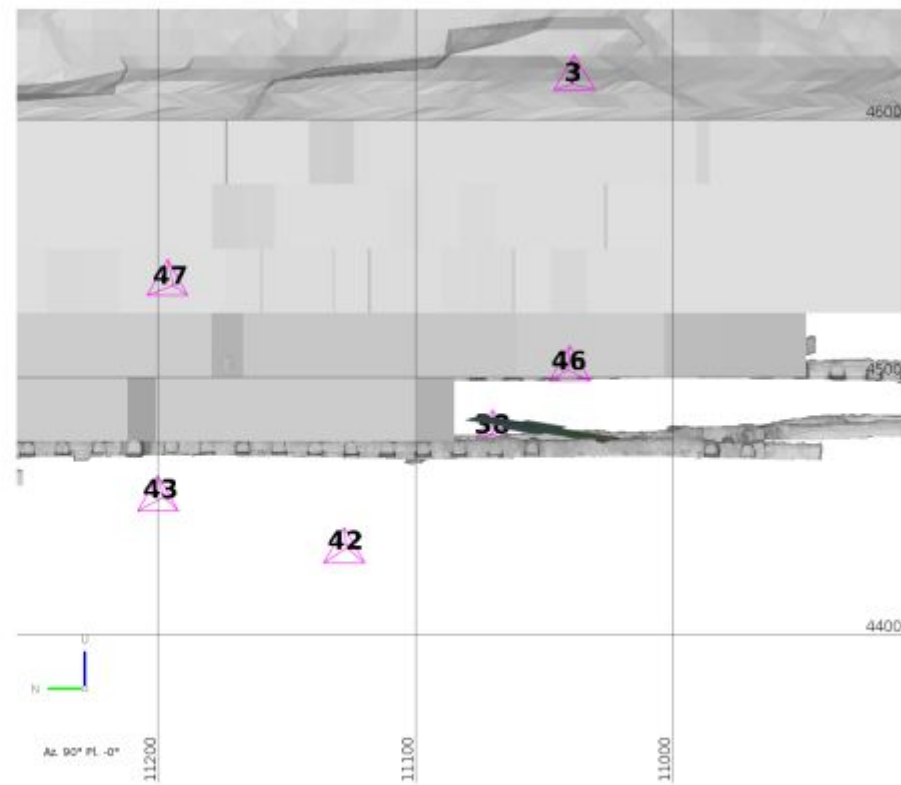
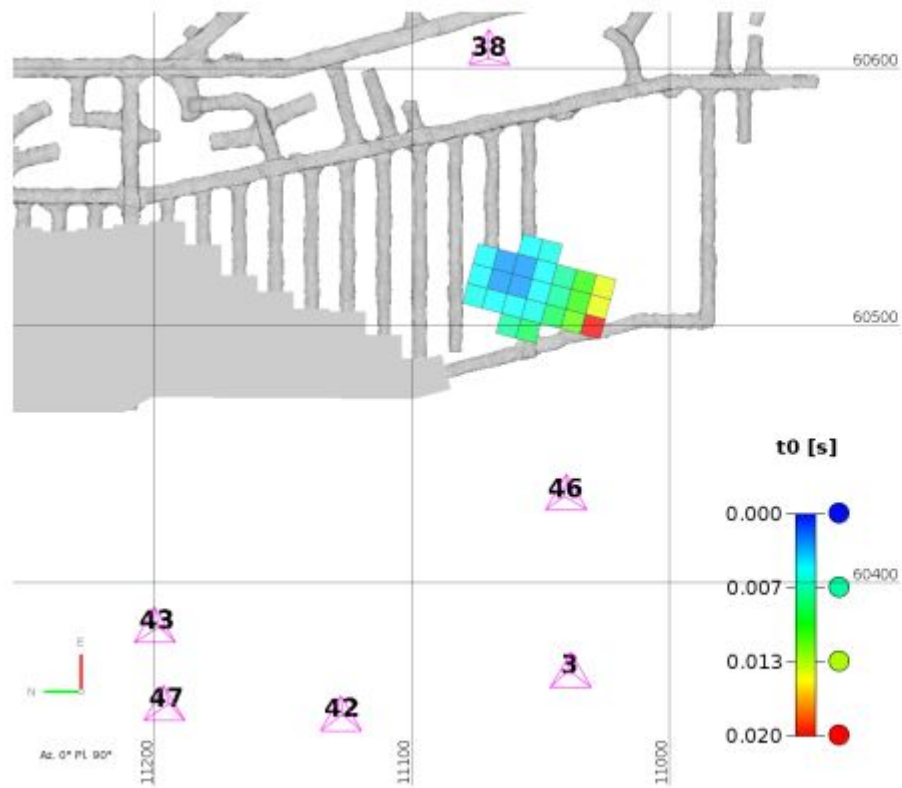
Caso de estudio A: Localización del inicio del proceso de ruptura y su incertidumbre



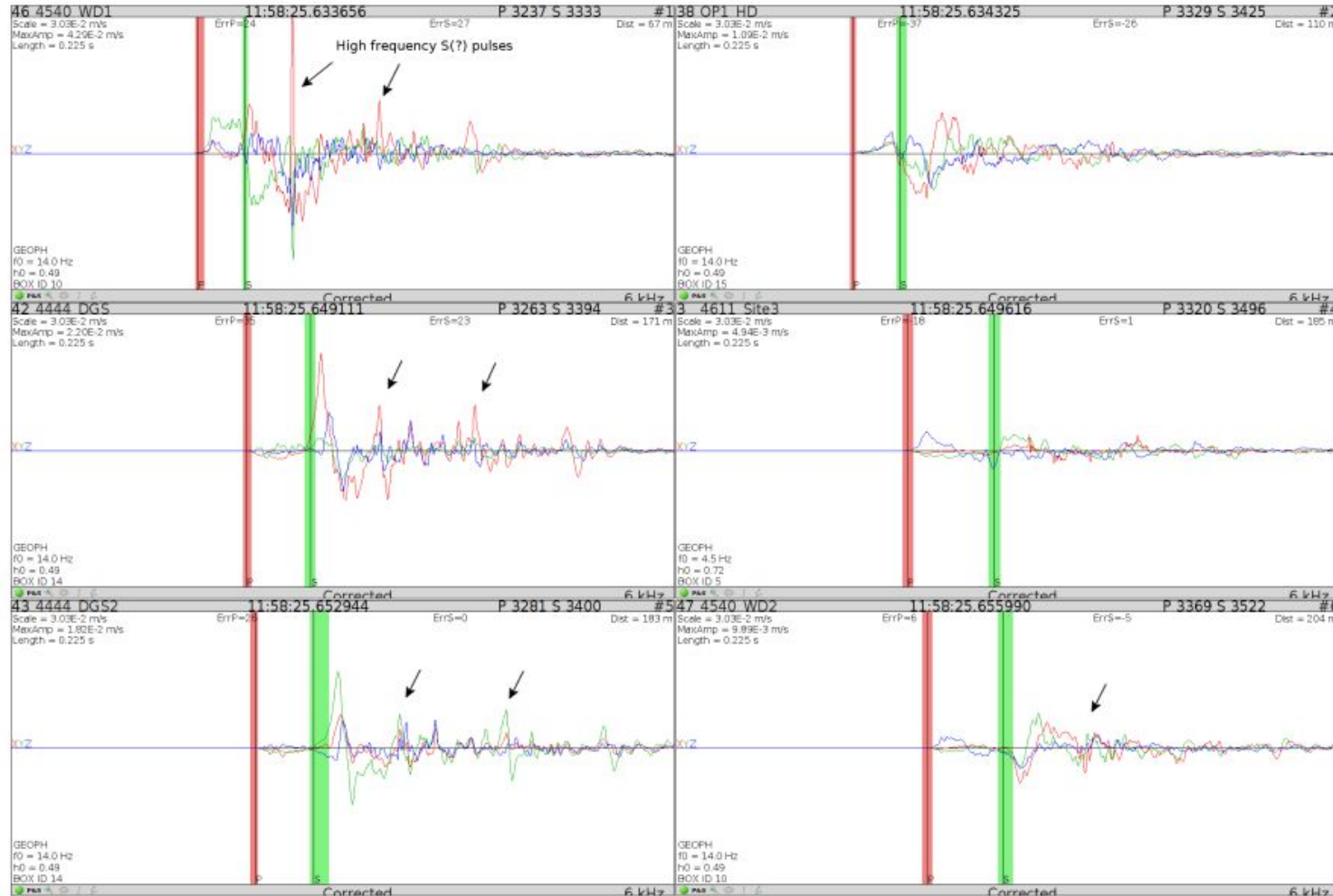
Caso de estudio A: Mecanismo de fuente



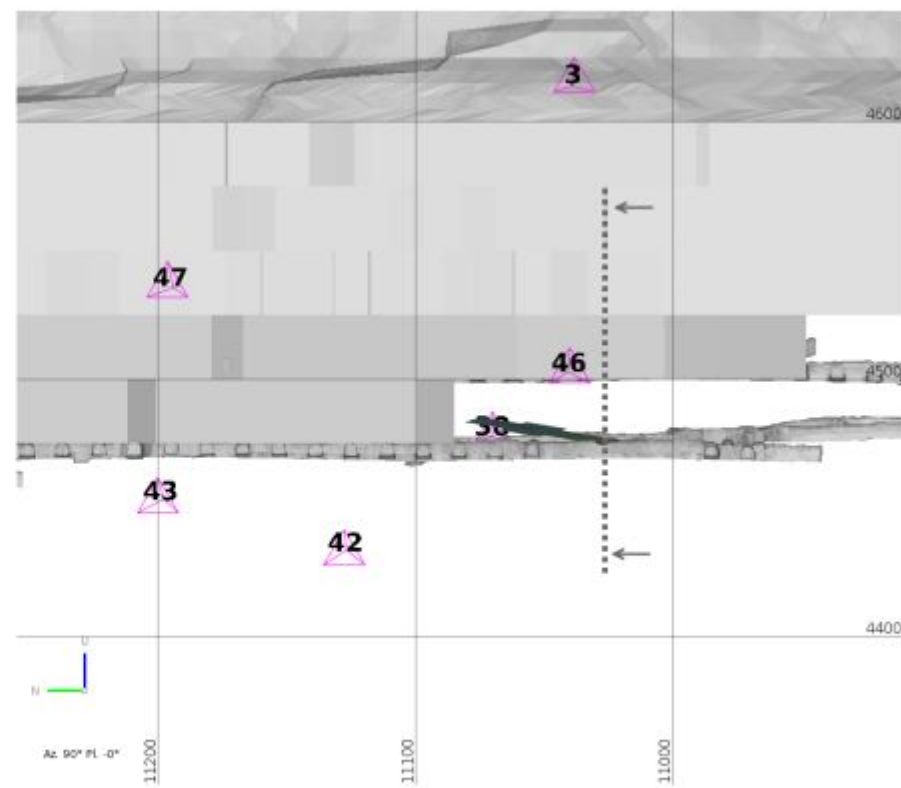
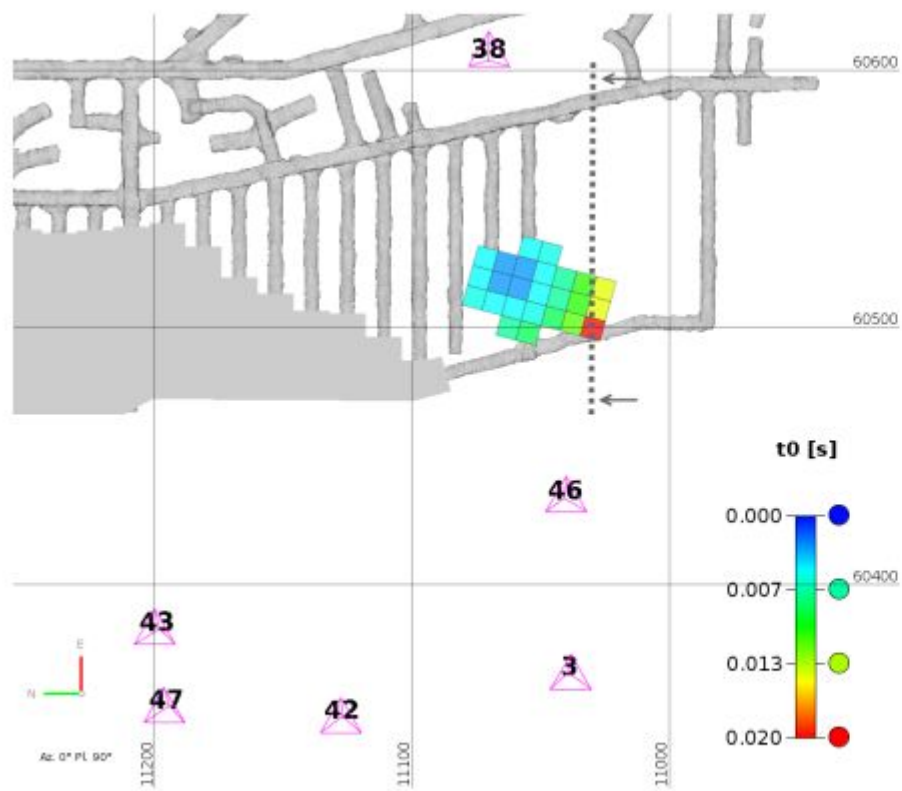
Caso de estudio A: Interpretación



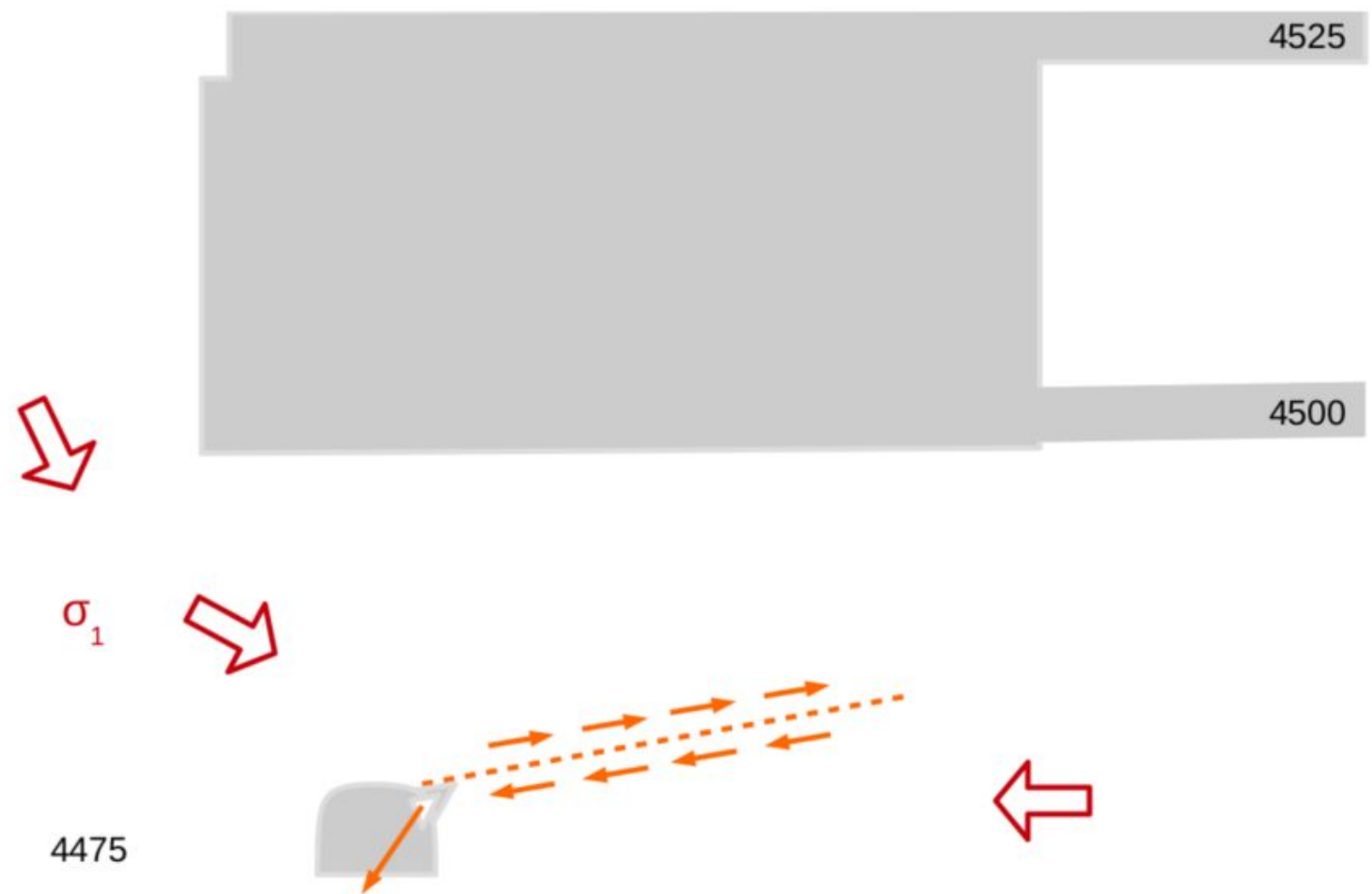
Caso de estudio A: Pulsos de alta frecuencia



Caso de estudio A: Interpretación

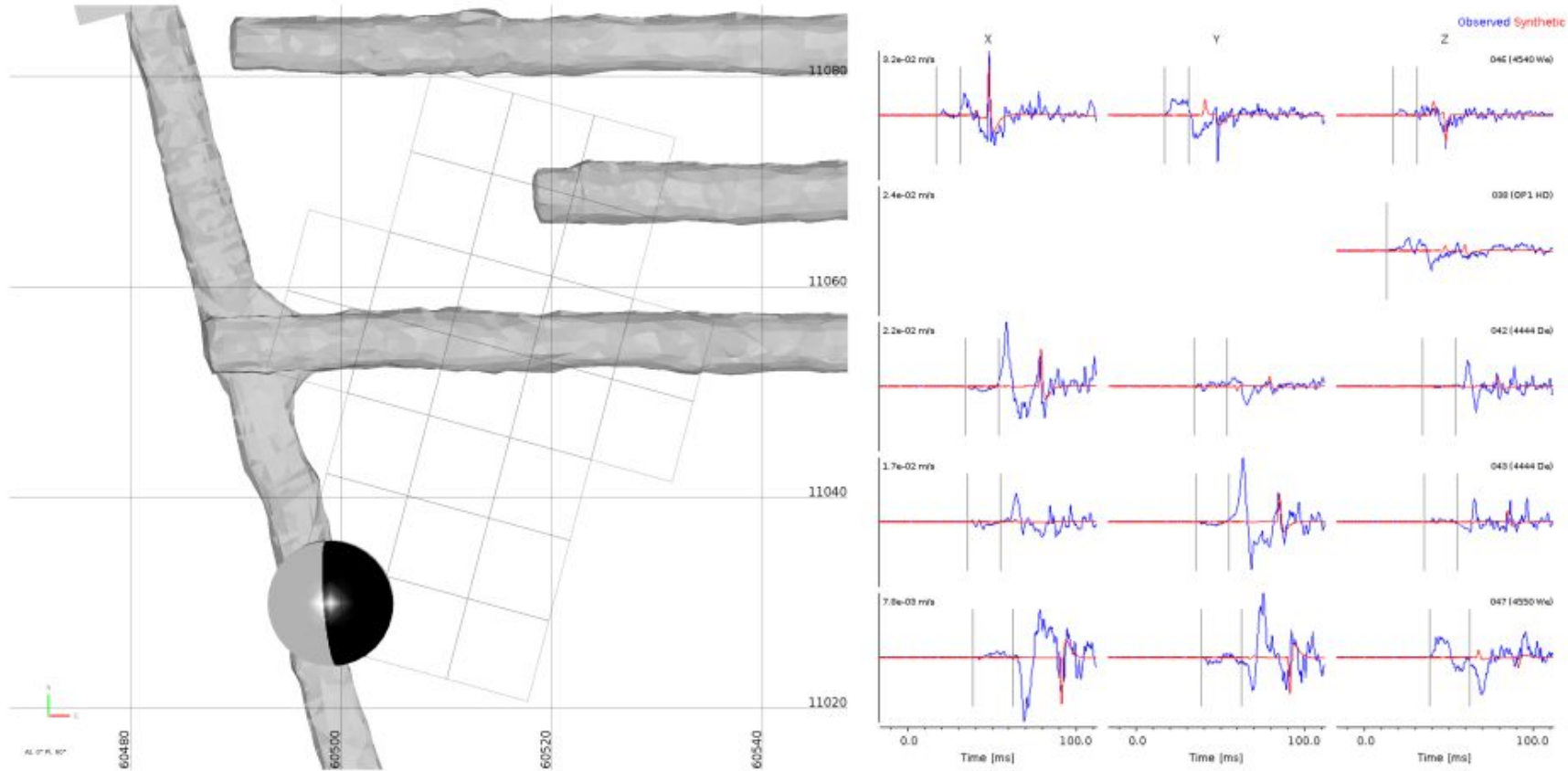


Caso de estudio A: Interpretación

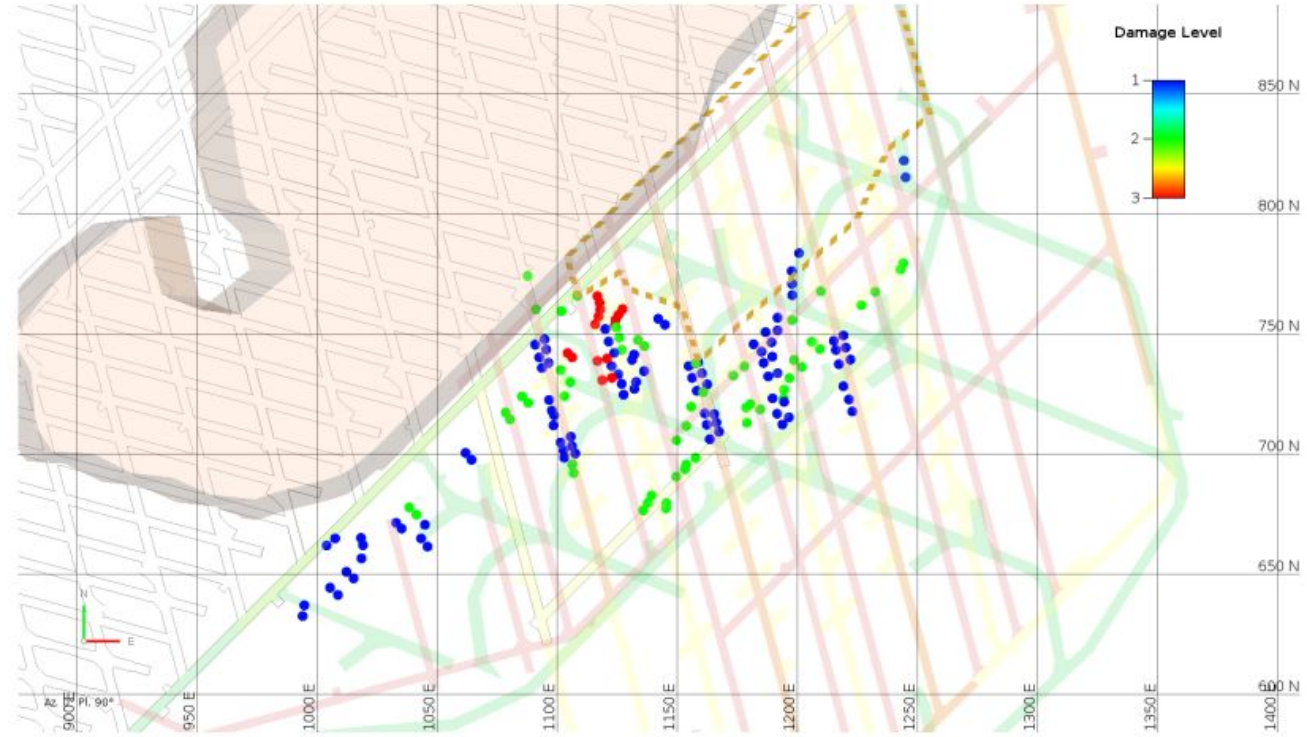


Caso de estudio A:

Parámetros de la sub-fuente: Potencia sísmica $P=1.1 \text{ m}^3$, $f_c=100 \text{ Hz}$. Considerando un elemento de deslizamiento de $8 \text{ m} \times 8 \text{ m}$, la velocidad de deslizamiento sería 1.72 m/s ($\text{PGV}=0.86 \text{ m/s}$). Sin embargo, el PGV calibrado por GMPE resulta en 0.052 m/s para $P=6.3 \text{ m}^3$ v distancia hipocentral de 40 m .



Caso de estudio B:



Level 1



Replacement of surface ground support elements is required

Level 2



Surface and reinforcement elements need to be replaced

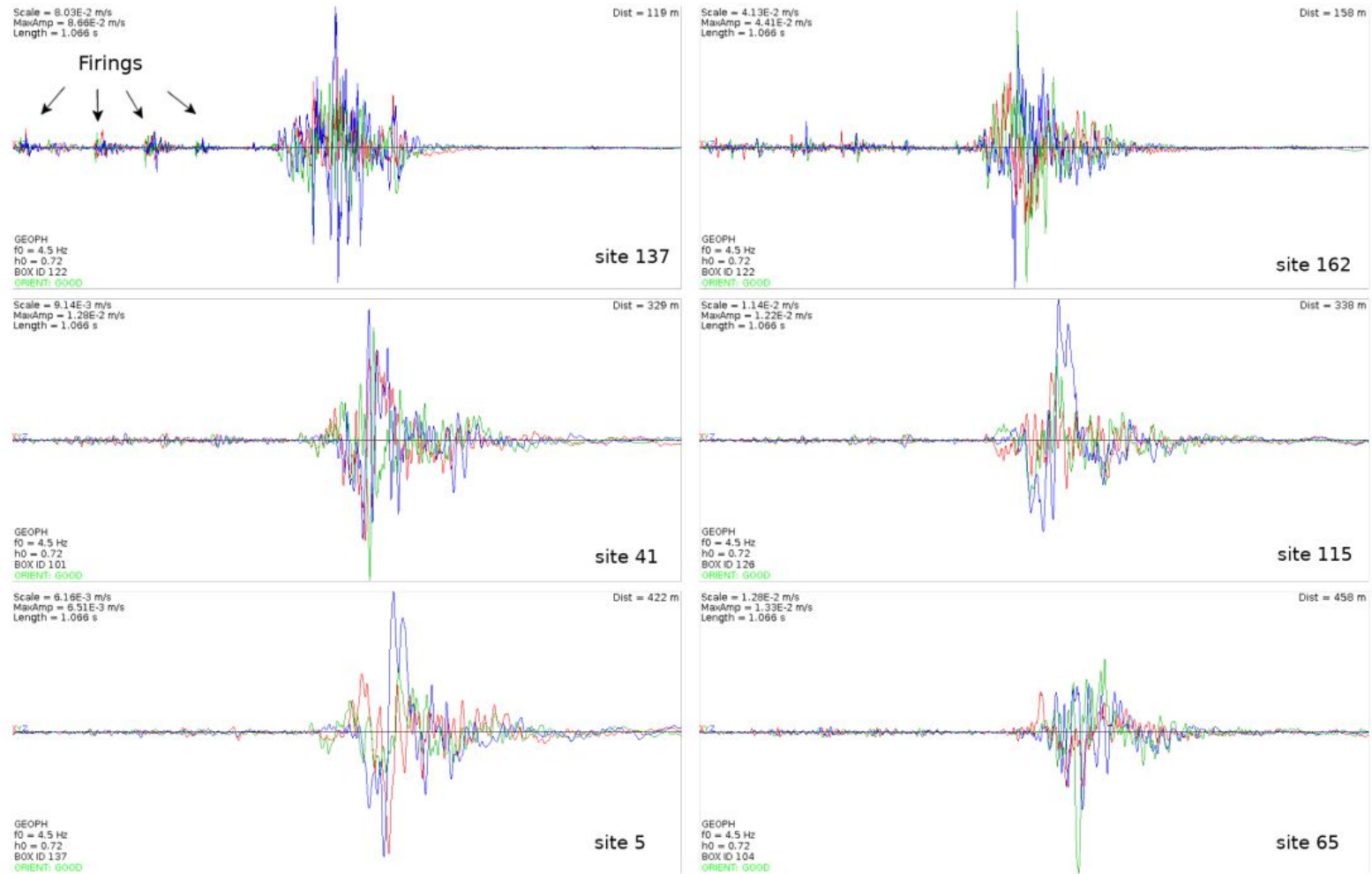
Level 3



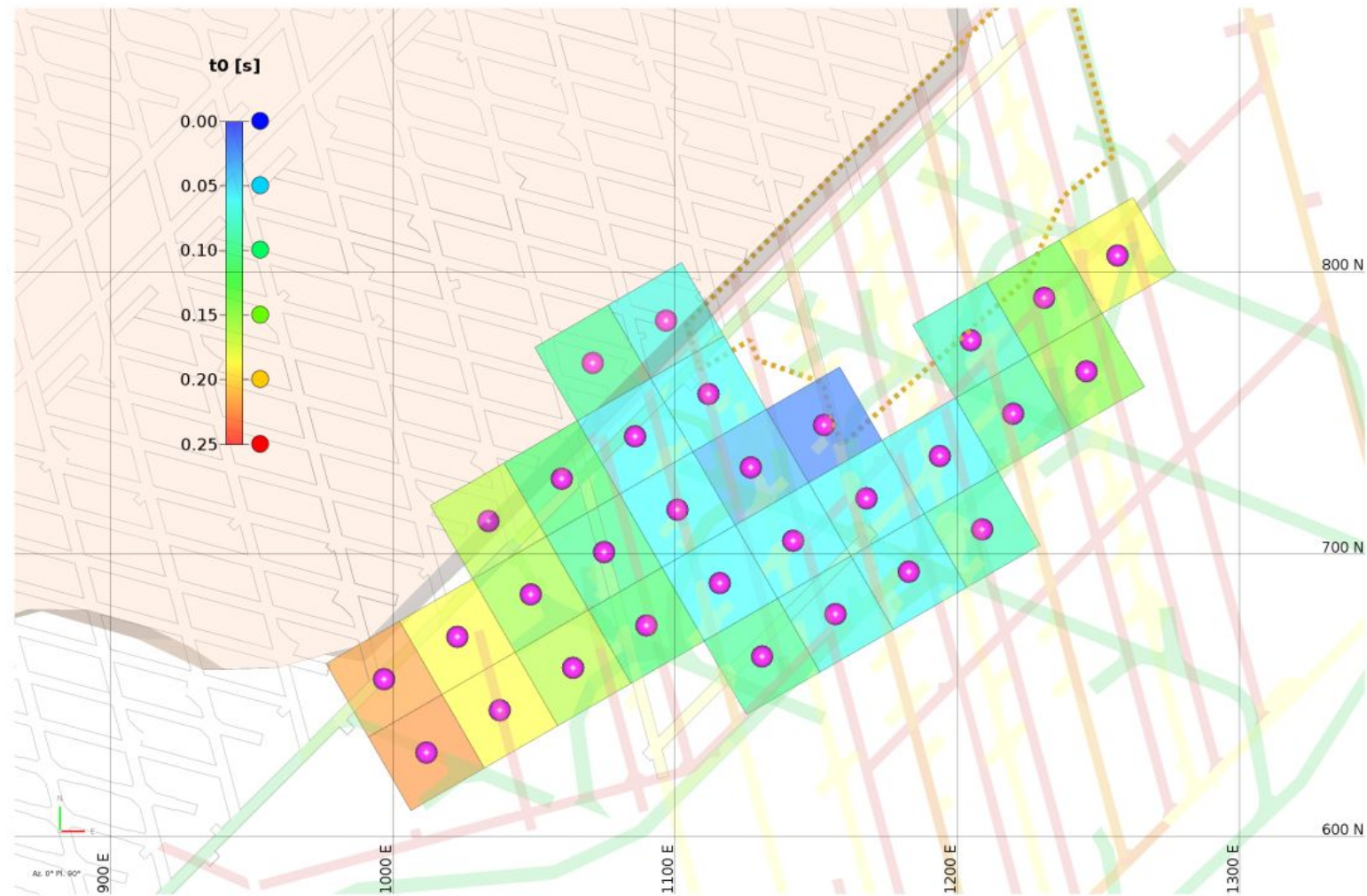
All support elements have been compromised. Rehabilitation is not possible sometimes or techniques such resin injections are required before attempting rehabilitation



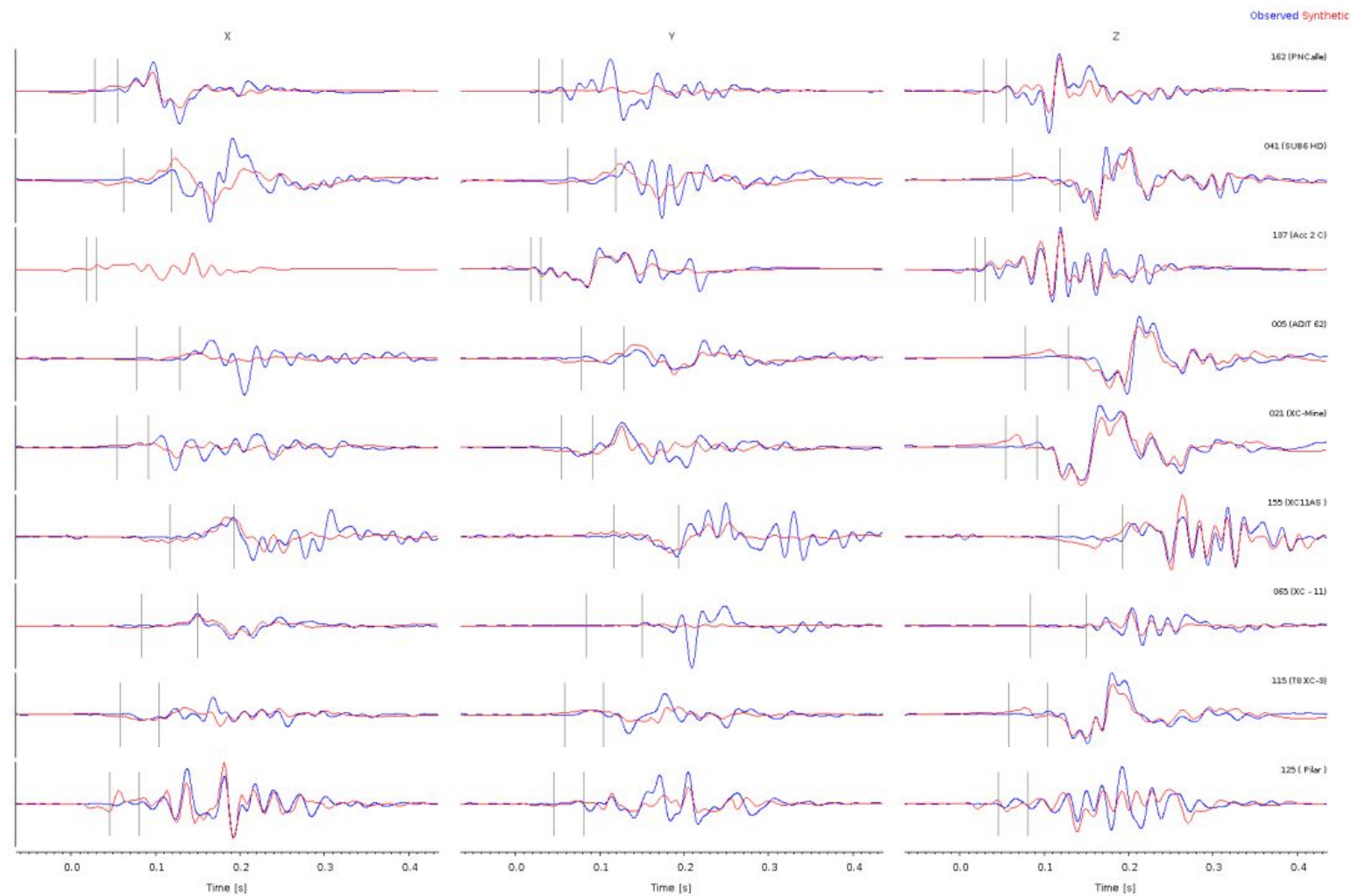
Caso de estudio B: Ondas



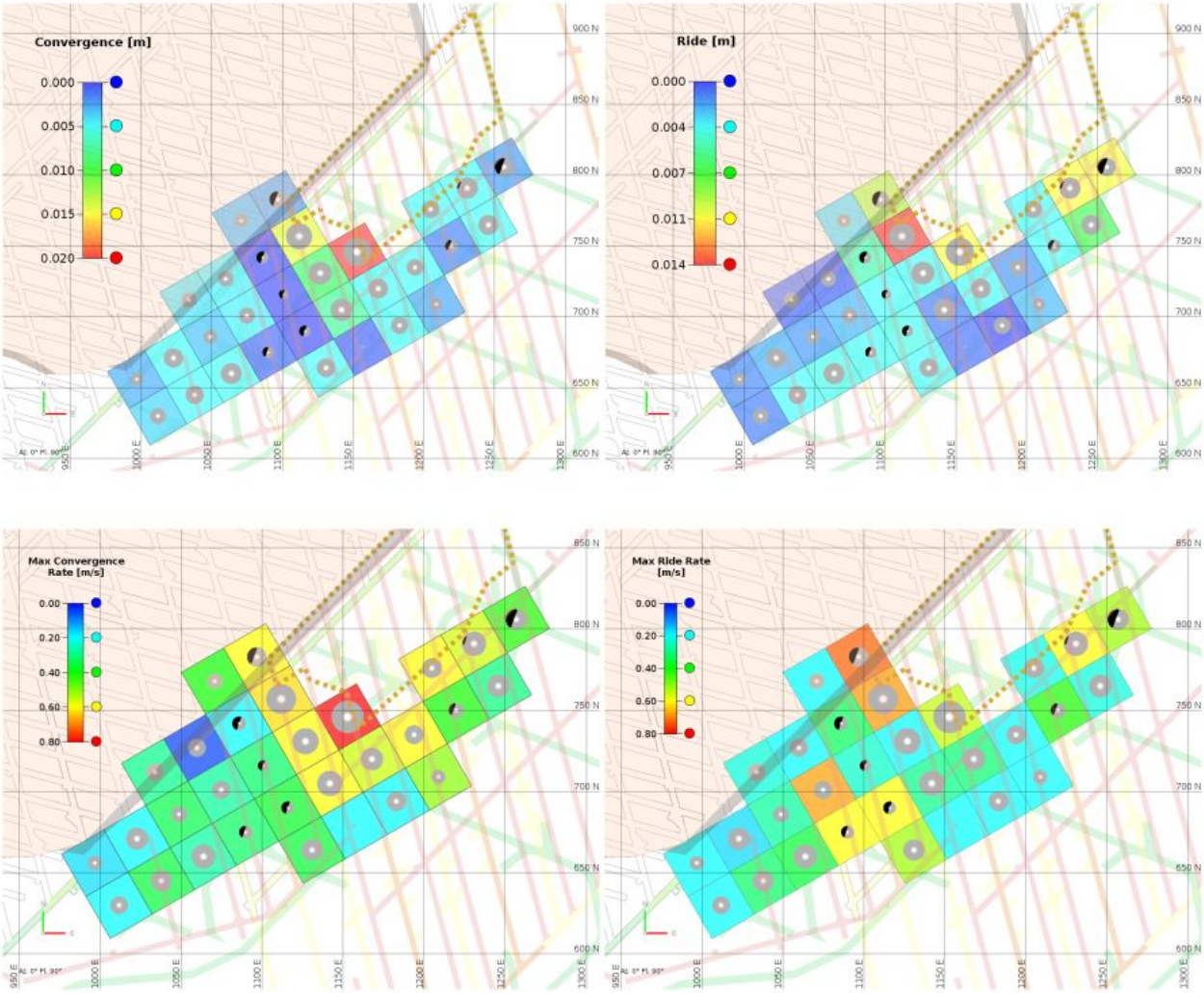
Caso de estudio B: Hipótesis de fuente compleja distribuida



Caso de estudio **B**: Ajuste entre ondas observadas y modeladas



Caso de estudio B: Reconstrucción de la secuencia de daño en los pilares



Puntos a resaltar:

- El monitoreo microsísmico tiene el potencial de brindar una oportunidad de análisis sísmico avanzado que ayuda en la validación de modelos geomecánicos.
- El análisis avanzando (mecanismos de fuente) brinda información de las direcciones de esfuerzos y sus variaciones espaciales y temporales.
- Es importante comprender la complejidad de fuentes ya que no todas se pueden describir con modelos de fuente puntual.
- Las fuentes complejas pueden emitir mayor energía en zonas diferentes durante el proceso de ruptura. Esto puede explicar que el daño no necesariamente se observa en el punto de inicio de ruptura.