15th US-China Oil & Gas Industry Forum第15届中美石油天然气工业论坛
Chongqing, China中国重庆
16-18 September 2015

DIRECT IMAGING OF FRACS, NATURAL FRACTURE NETWORKS, AND PRODUCING VOLUMES WITH PASSIVE SEISMIC DATA

根据被动地震数据对压裂裂缝，天然裂缝以及成产体积进行直接成像

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Direct imaging of SRV, induced fractures & stimulated natural fractures as complex surfaces & networks

使用复杂的表面以及网格对储层改造体积、压裂改造裂缝和改造的天然裂缝进行直接成像

Cloud: Direct image of SRV of a single frac stage.

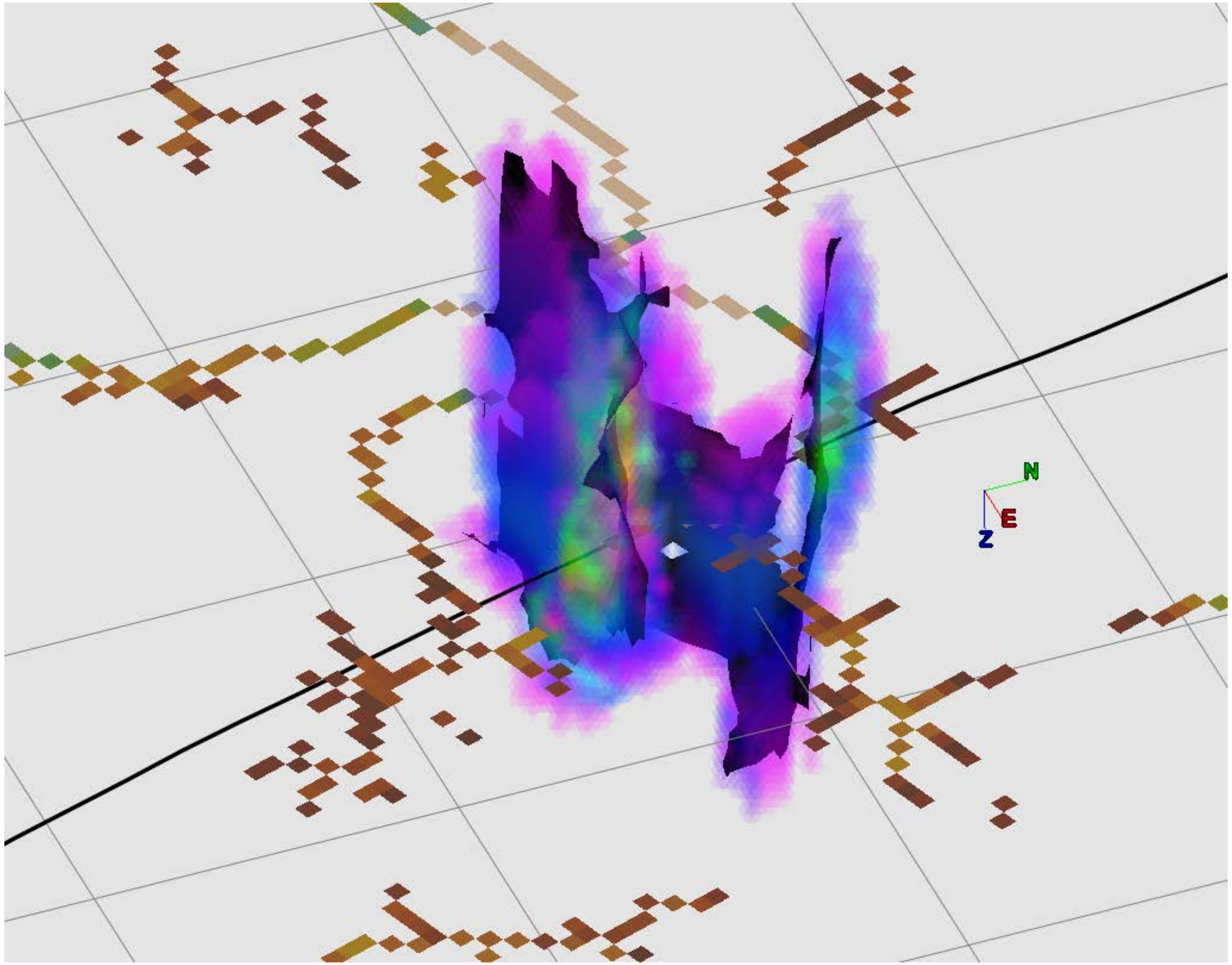
云：一个单独压裂段的储层改造体积的直接成像

Surface within the cloud: Main fracture surfaces.

云表面：主要裂缝表面

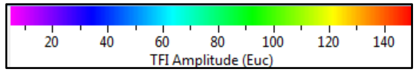
Sepia: Slice of direct image of natural fractures stimulated by the frac.

深褐色：由压裂改造的天然裂缝的直接成像切片



Marcellus Fm.
500 ft grid

Direct imaging of hydraulic fracture – movie
水力压裂直接成像-电影



250 ft

Passive seismic monitoring through the unconventional life cycle
贯穿非常规活动周期的被动地震监测

Before • During • After

压裂前• 中• 后

Before – Before well completion or even before drilling a well, map the natural fractures.

压裂前-完井之前甚至钻井之前的天然裂缝成像

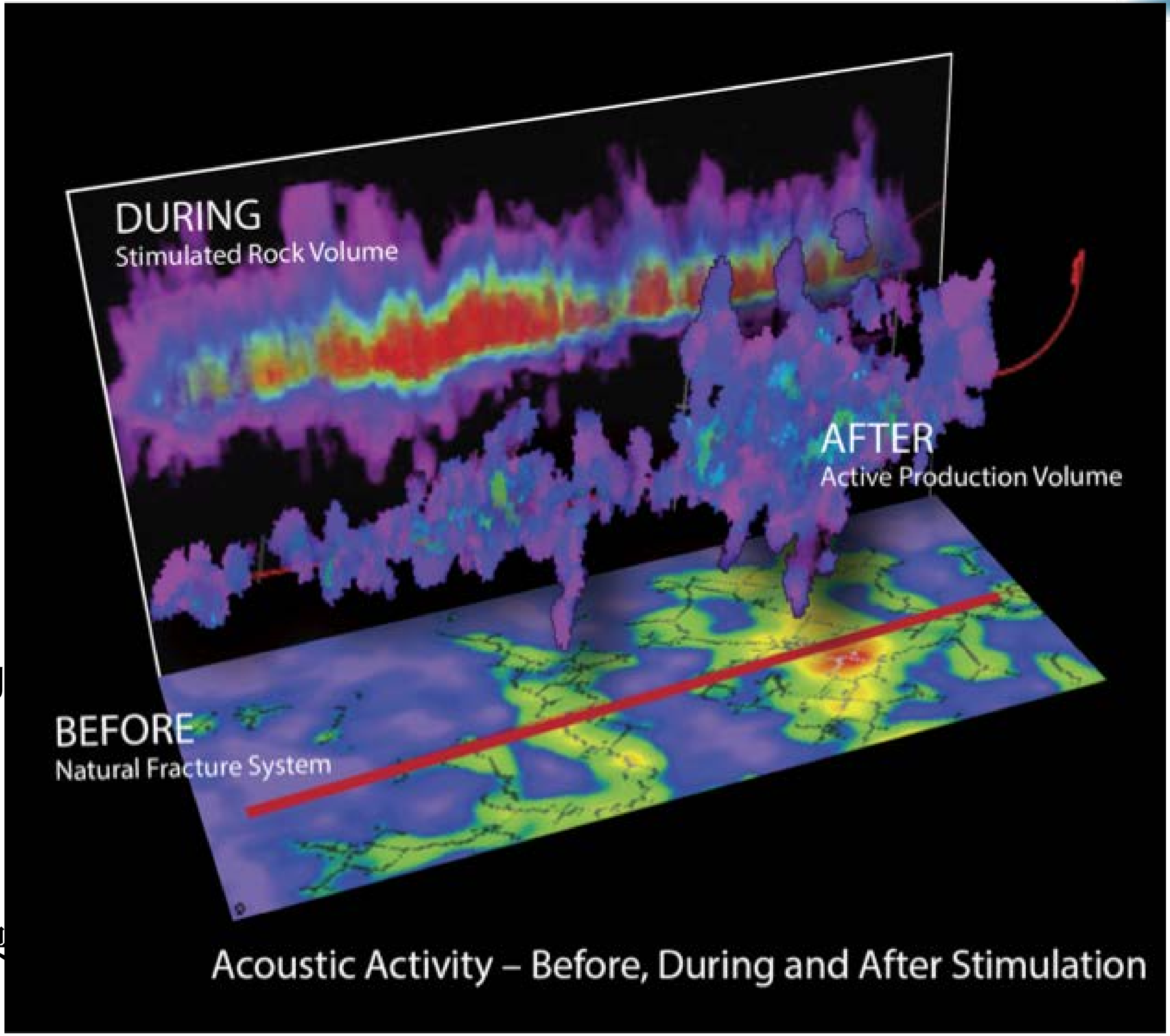
During – Image the effect of stimulation. Map interactions between wells.

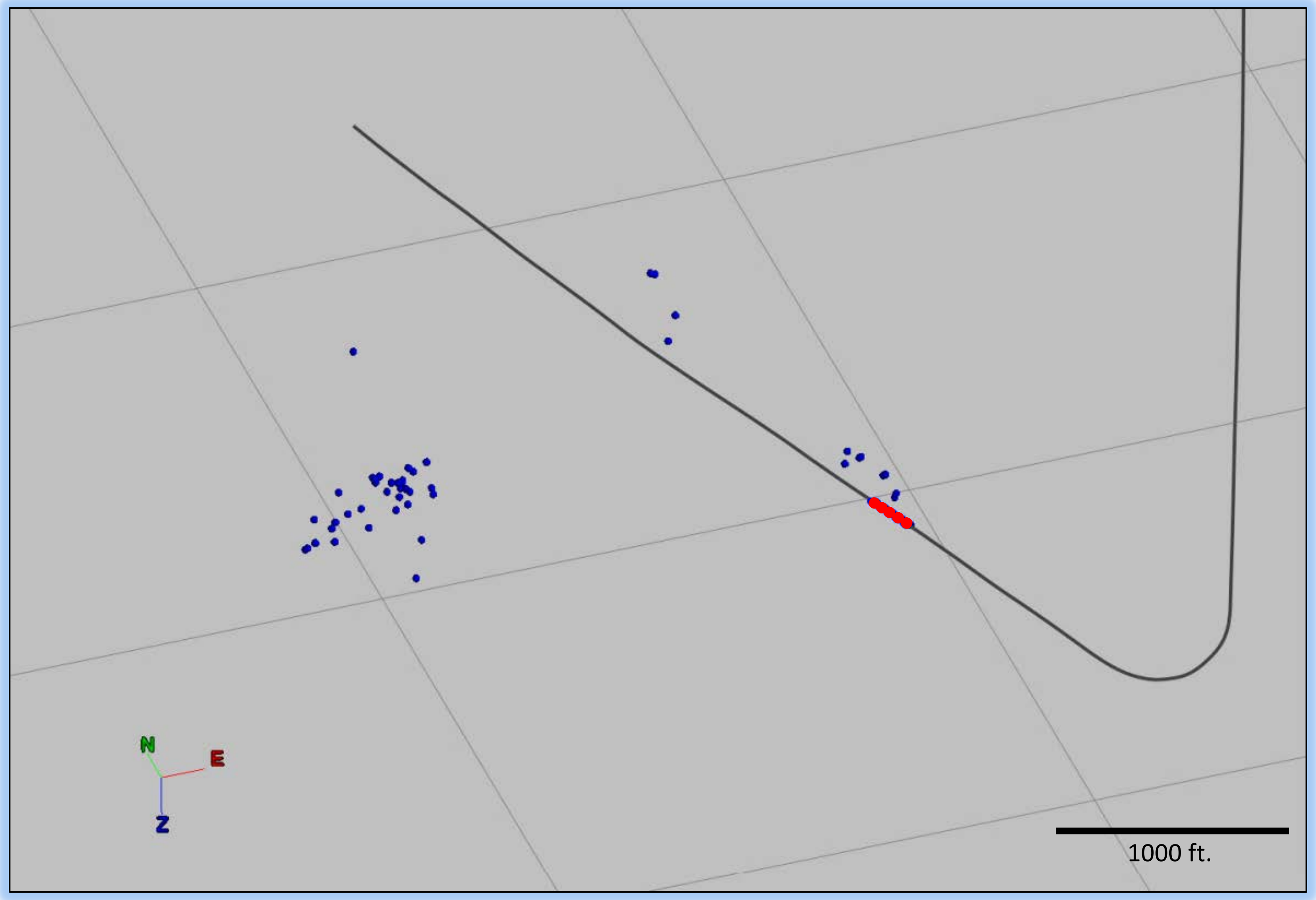
压裂中-改造效果的成像。井间地图交互。

After – Monitor changes in the reservoir during production.

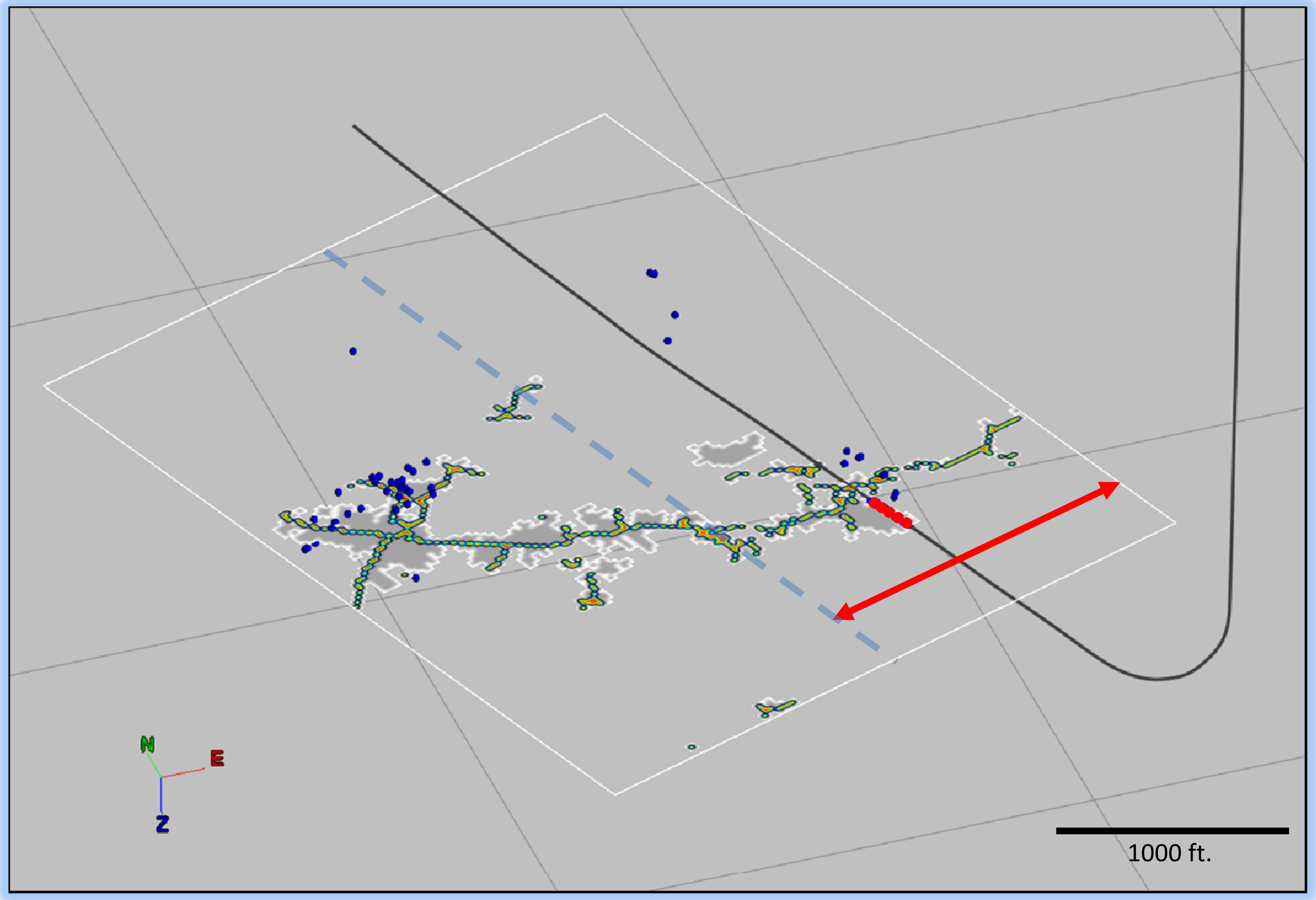
压裂后-监测生产过程中储层的变化

Products are computed directly from the recorded field data.通过野外记录数据直接计算结果





Eagle Ford example. Oblique view of wellbore with microearthquake hypocenters (blue dots). Red dots on the wellbore are the perf clusters.
Eagle Ford实例：井筒和微地震震源（蓝点）倾斜视角。井筒上红点是射孔簇。



Eagle Ford example. Hypocenters (blue dots) and slice of the ***Tomographic Fracture Image™*** at depth of the wellbore. Red dots are perf locations.
Eagle Ford实例。震源（蓝点）和井筒深度处的*裂缝层析成像*™切片。红点为射孔簇。

Generating Tomographic Fracture Images℠

生成裂缝层析成像℠

How Tomographic Fracture Imaging℠ works 裂缝层析成像℠机理

STEP 1: Seismic Emission Tomography (SET)

步骤1：地震发射层析成像（SET）

- ESTABLISHED SCIENCE
- 已存在的科学
- WIDELY USED广泛的应用

1. Deploy surface array, acquire.地表排列和采集
2. Develop velocity model, preliminary processing: statics, noise removal etc.
   建立速度模型，预处理：静校正，噪音移除等。
3. Define study volume, build travel-time table from every voxel to every receiver.
   确定研究区域，建立每个体元到每个检波器的旅行时表格
4. Voxel-by-voxel, align traces & compute semblance (or other measure) in small, overlapping time-steps. Result is a 5D data volume (X, Y, Z, time-step, semblance)
   每个体元，较平道集并计算相似值（或其它测量值），叠加时间步长。产生五维数据体（XYZ,时间步长，相似值）

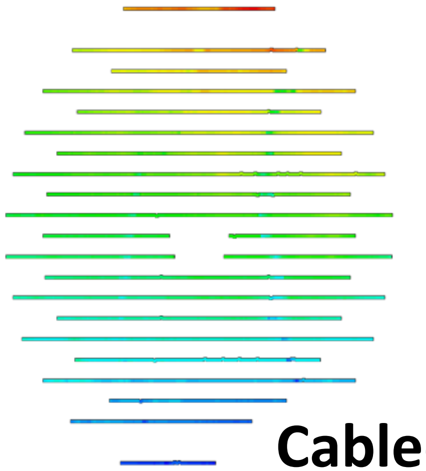
STEP 2: Tomographic Fracture Imaging℠ (TFI)

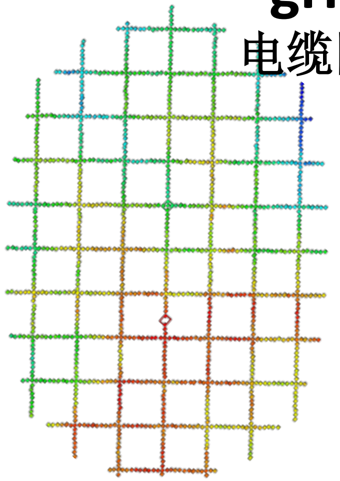
步骤2：裂缝层析成像℠ (TFI)

5. Sum timesteps over period of interest to cancel random noise and stack signal.
   叠加所有有用的时间步长来消除随机噪音并且叠加信号
6. Clip data to eliminate residual noise leaving high energy clouds
   切除数据用于消除剩余噪音得到高能量云 .
7. Find maximum activity surfaces of high energy clouds. 寻找高能量云最活跃表面

NEW, PATENTED
新型，专利

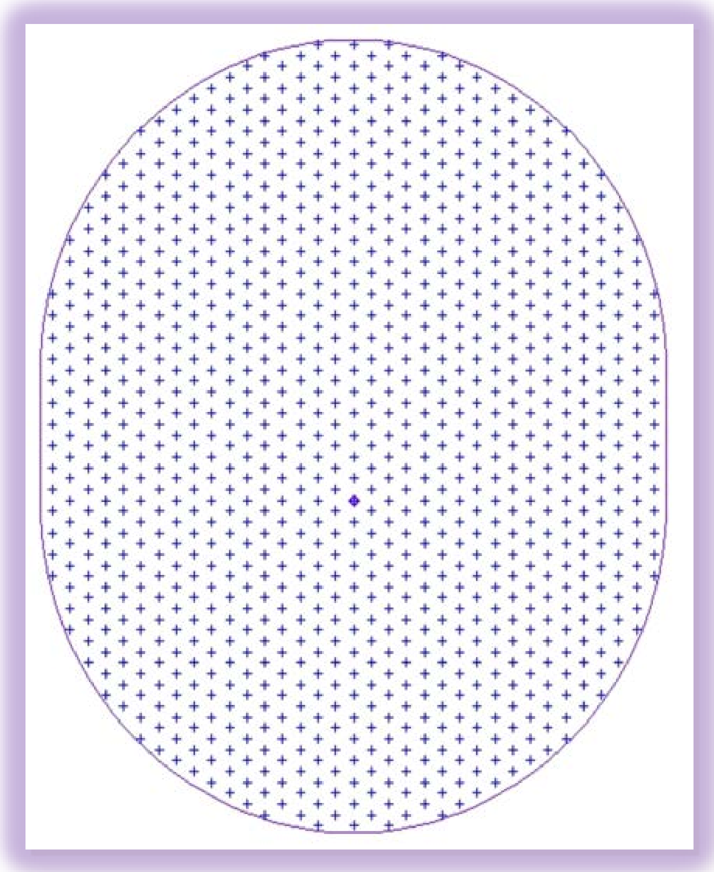
Acquisition - Uniform grids allow for optimal noise suppression
采集-均匀网格产生最佳噪音压制

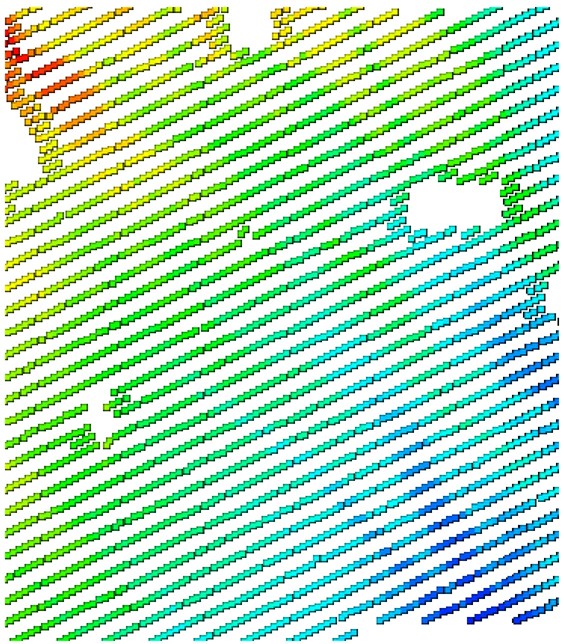




Cabled grids
电缆网格

Ideal Grid – Hexagonal
理想网格-六角形





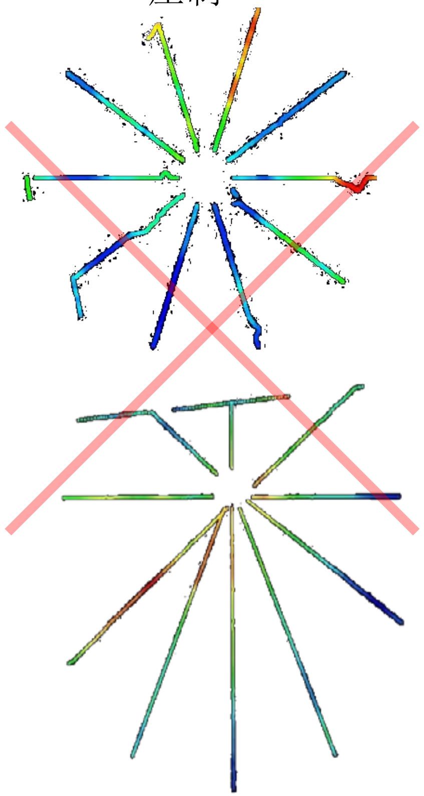
Passive Recording Using Active Acquisition Grid
被动监听应用灵活采集网格

Star-shaped grids

Non-uniform, poor sampling, difficult to suppress noise

星形网格

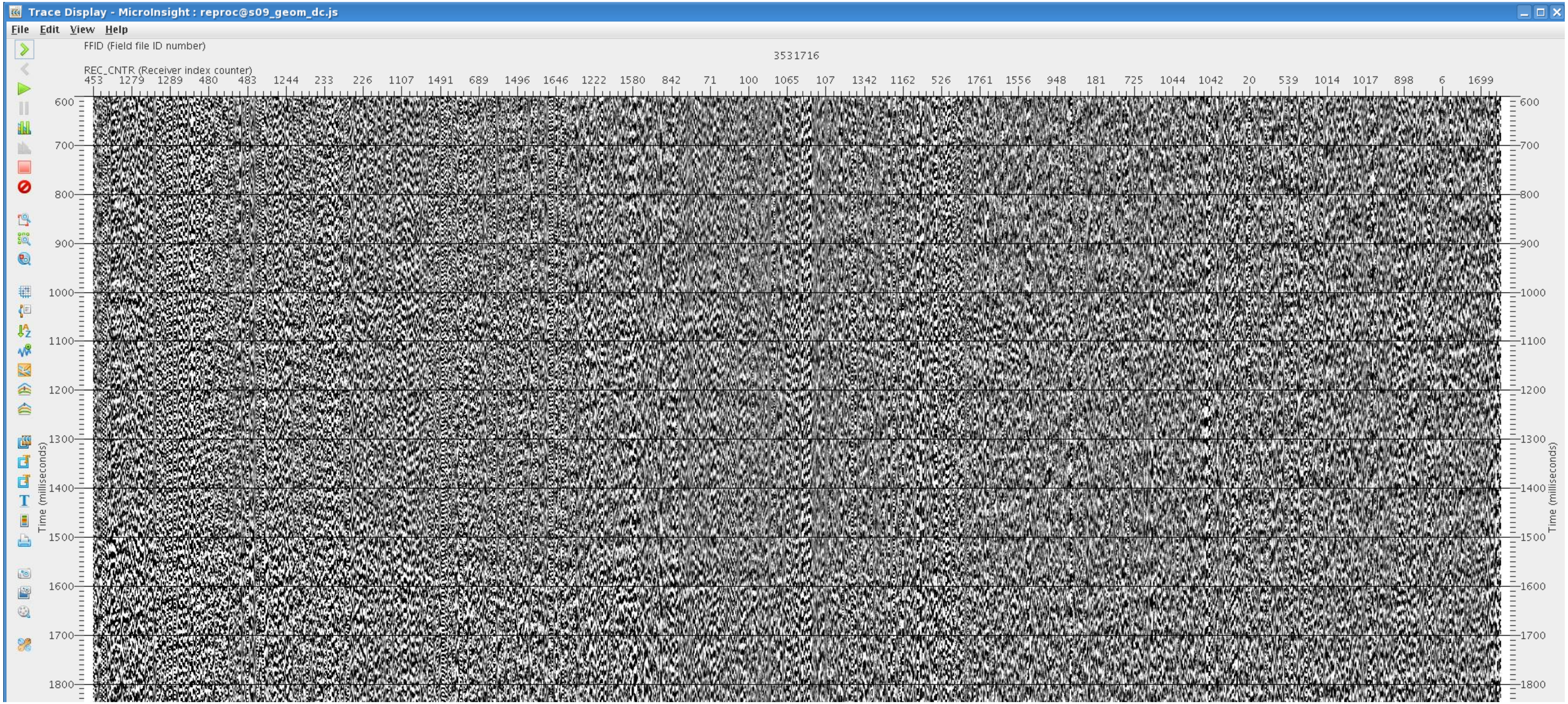
非均匀，低采样不利于噪音压制



TRACE PROCESSING: Trace view of MEQ with only DC debias and moveout

Sorted by azimuth

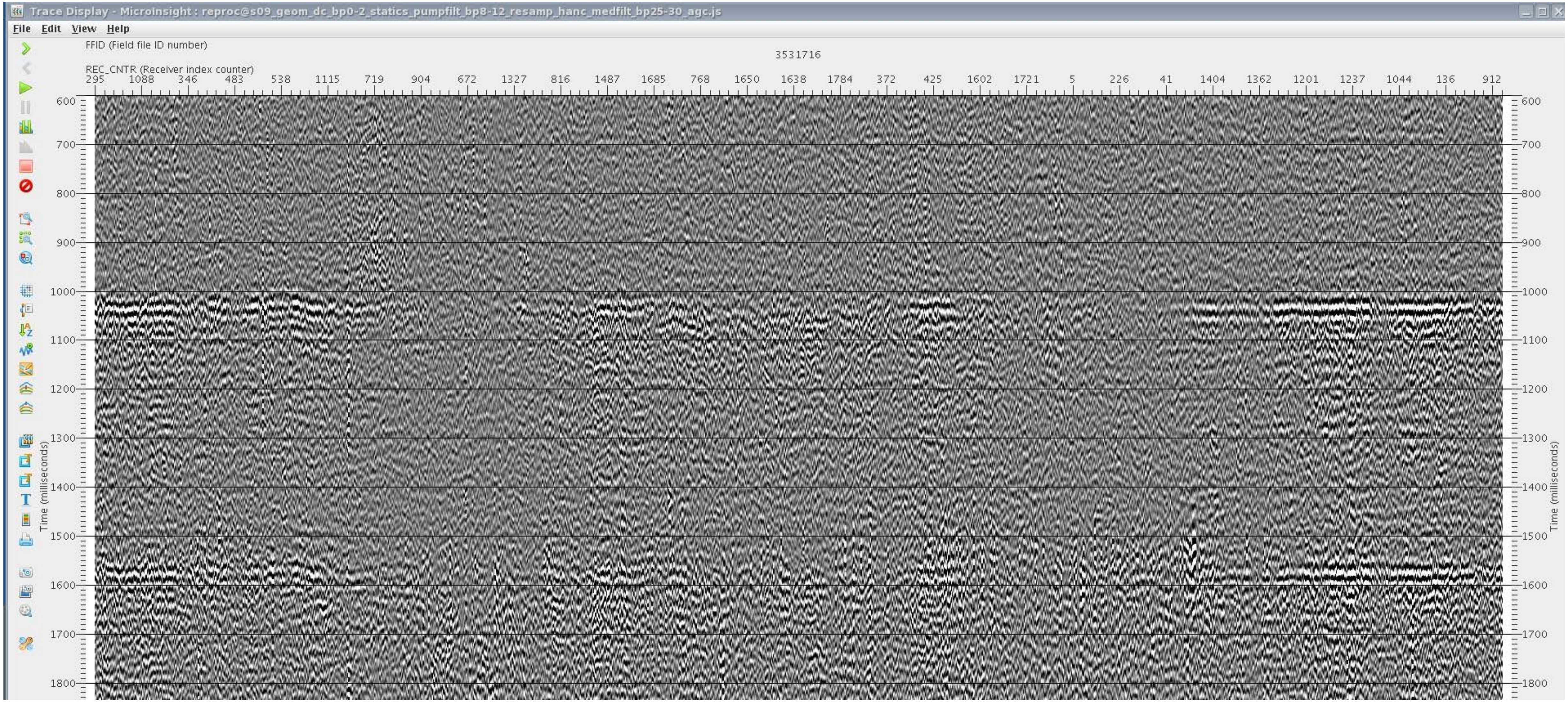
道集处理：由方位角分类，仅通过DC偏移和动校正的微地震道集信号



TRACE PROCESSING: After noise removal

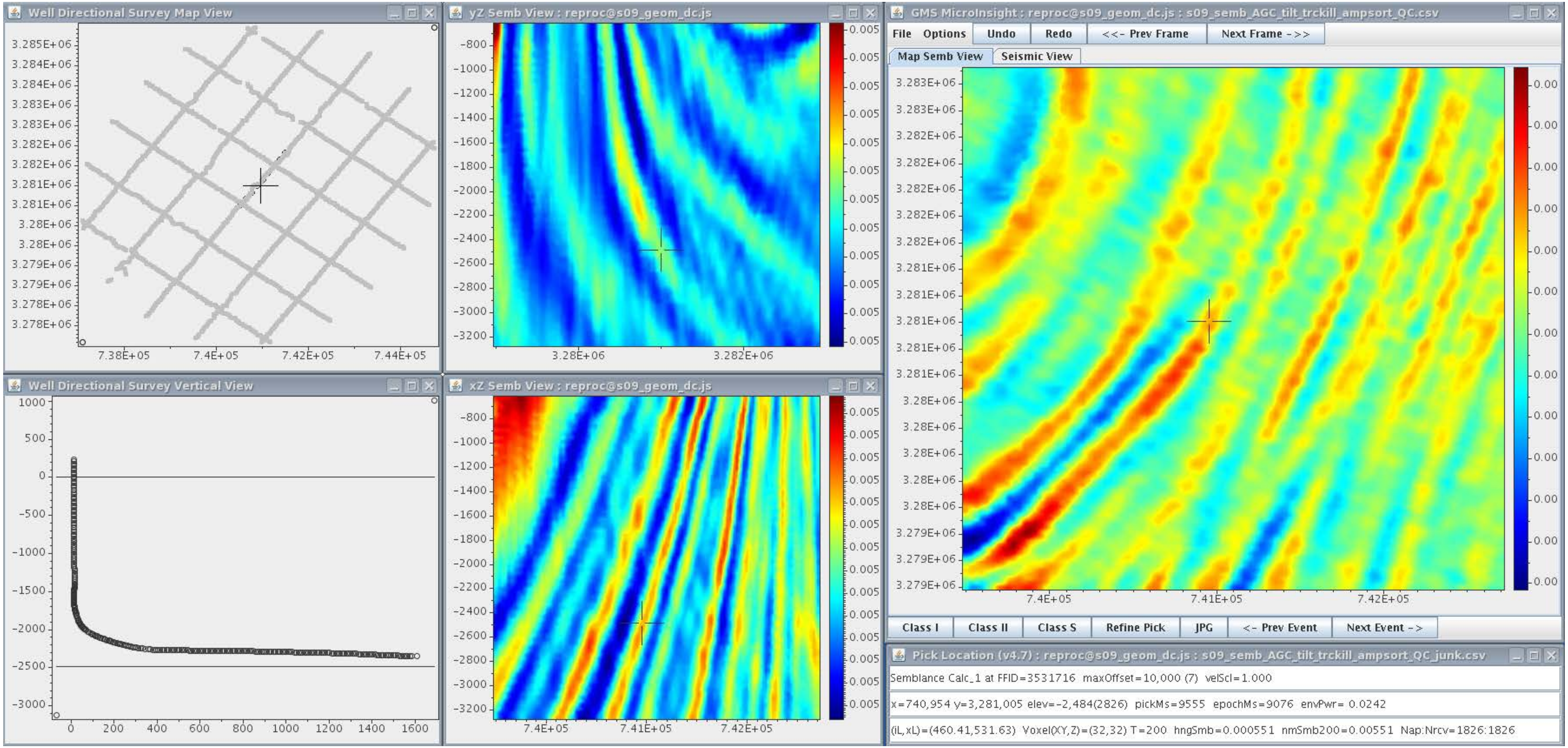
Sorted by azimuth

道集处理：由方位角分类，噪音移除后



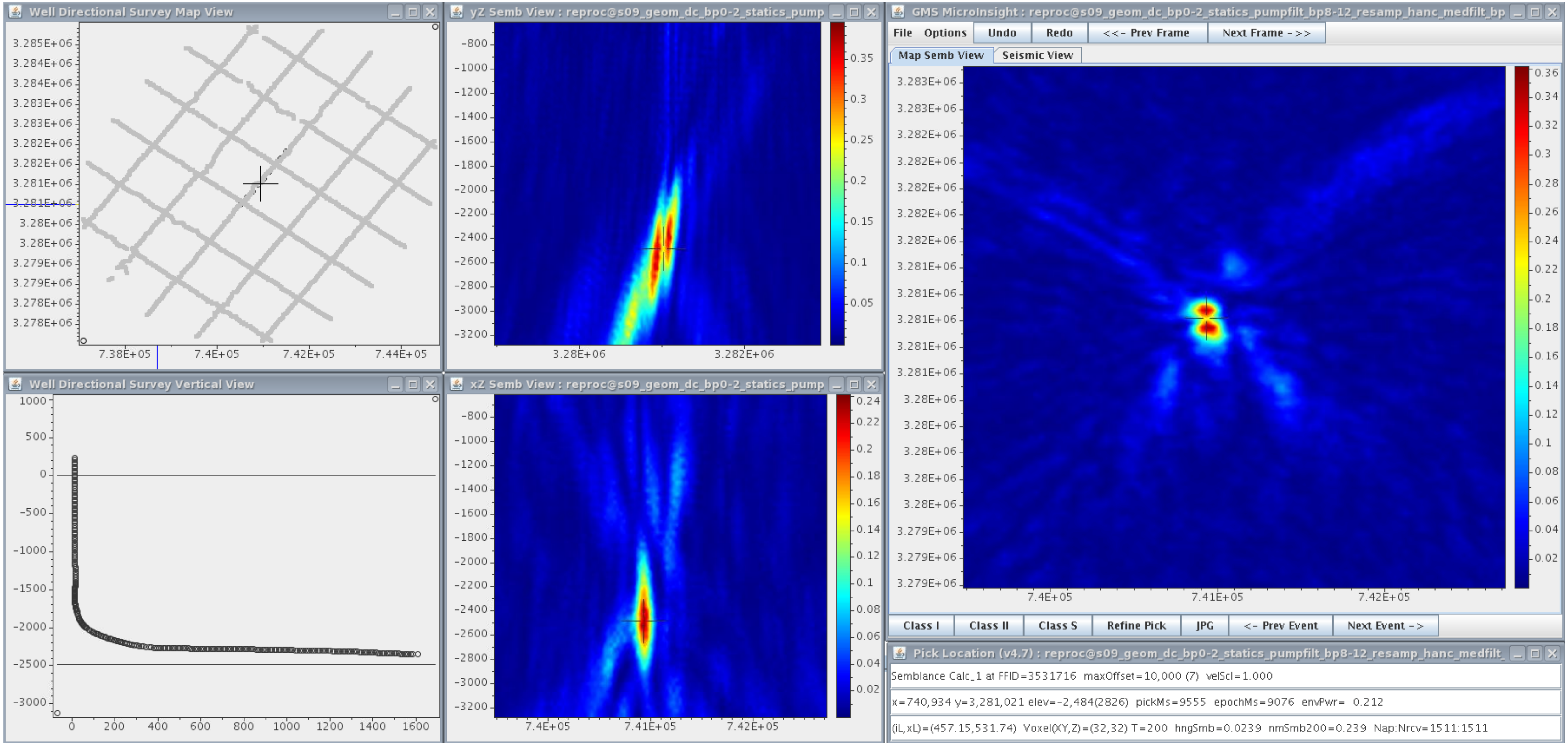
TRACE PROCESSING: Semblance plot with only DC debias and moveout

道集处理：仅通过DC偏移和动校正的相似值切片



TRACE PROCESSING: Semblance plot after noise removal

道集处理：噪音移除后相似值切片



Fracture Fairways their Damage Zones & Microseismicity

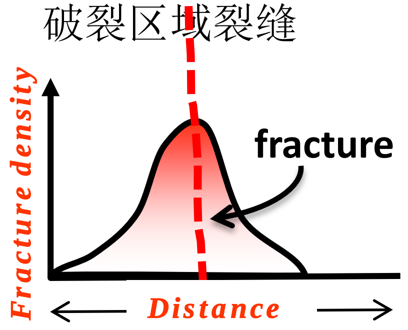
裂缝通道

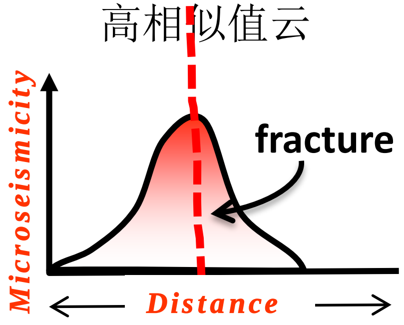
fracture with damage zone

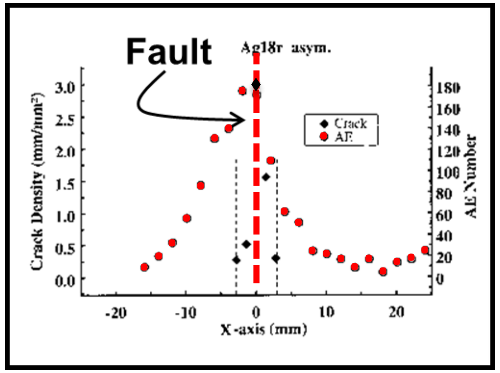
破裂区域

high-semblance cloud

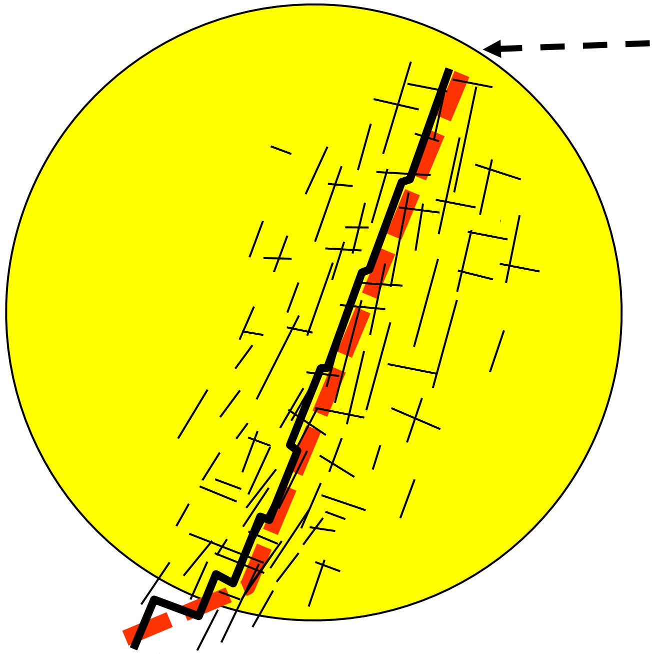
微地震

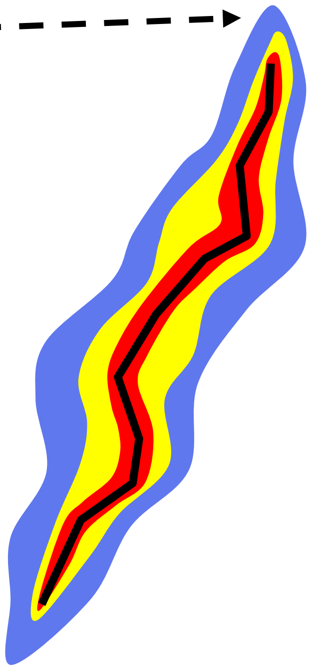






Janssen et al. 2001





Crack Density and seismicity

裂缝密度和相似值

High高

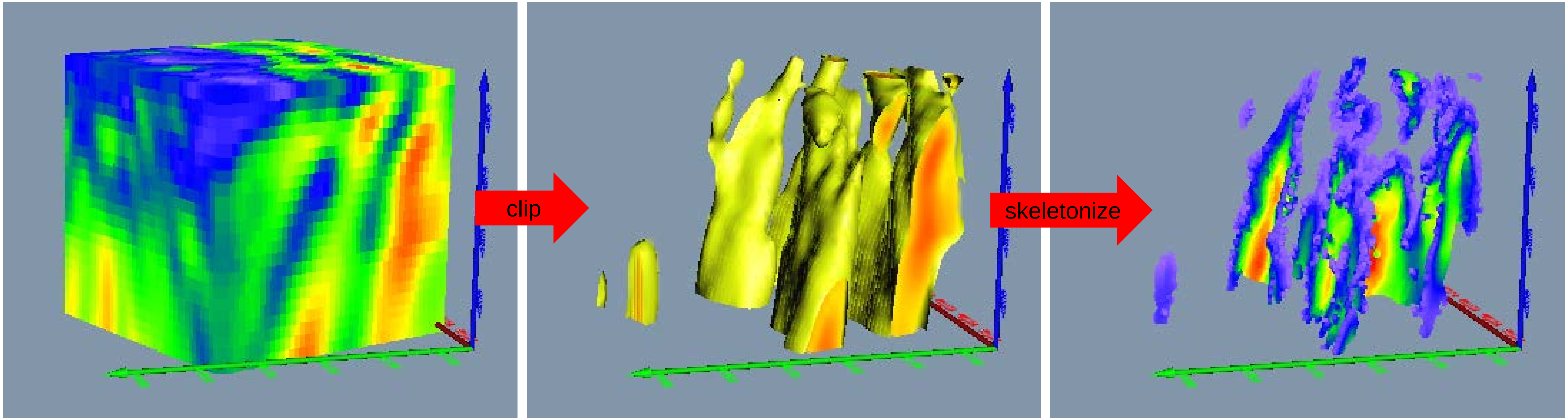
Low低

SUMMATION INCREASES S/N, SUPPRESSES RANDOM NOISE, REVEALS FRACTURES
叠加提高信噪比，压制随机噪音，生成裂缝

FRACTURE + NOISE
裂缝+噪音

NOISE ONLY
只有噪音

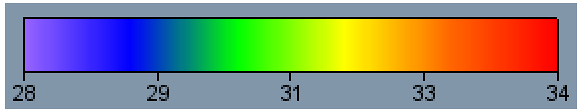
Generating a raster TFI from the stacked semblance volume
通过叠加的相似体产生光栅TFI



3D stacked volume
叠加的三维体

Clipped stacked volume
(high-semblance cloud)
切除后的叠加体
（高相似值云）

TFI (discrete fractures)
裂缝层析成像（离散裂缝）

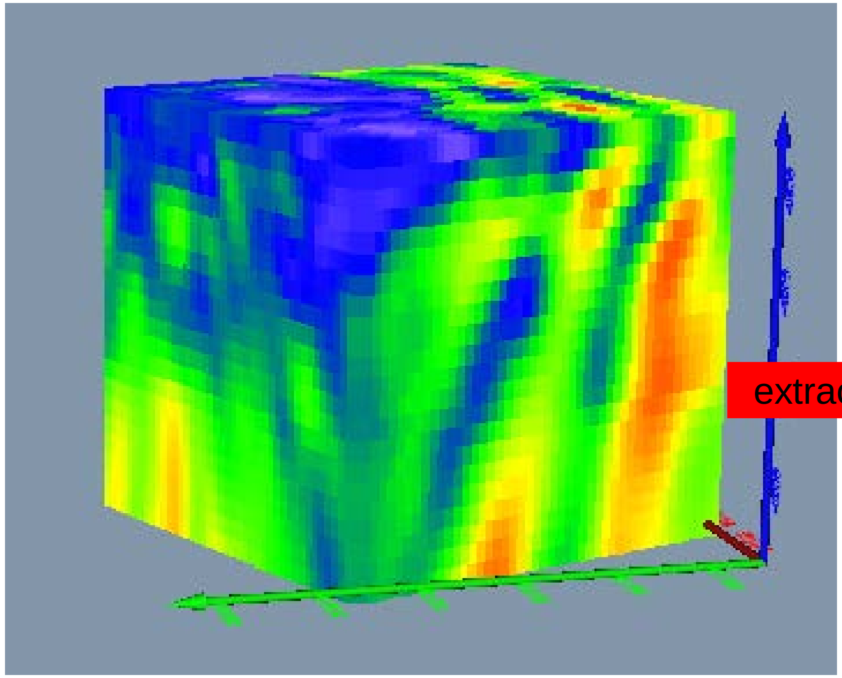


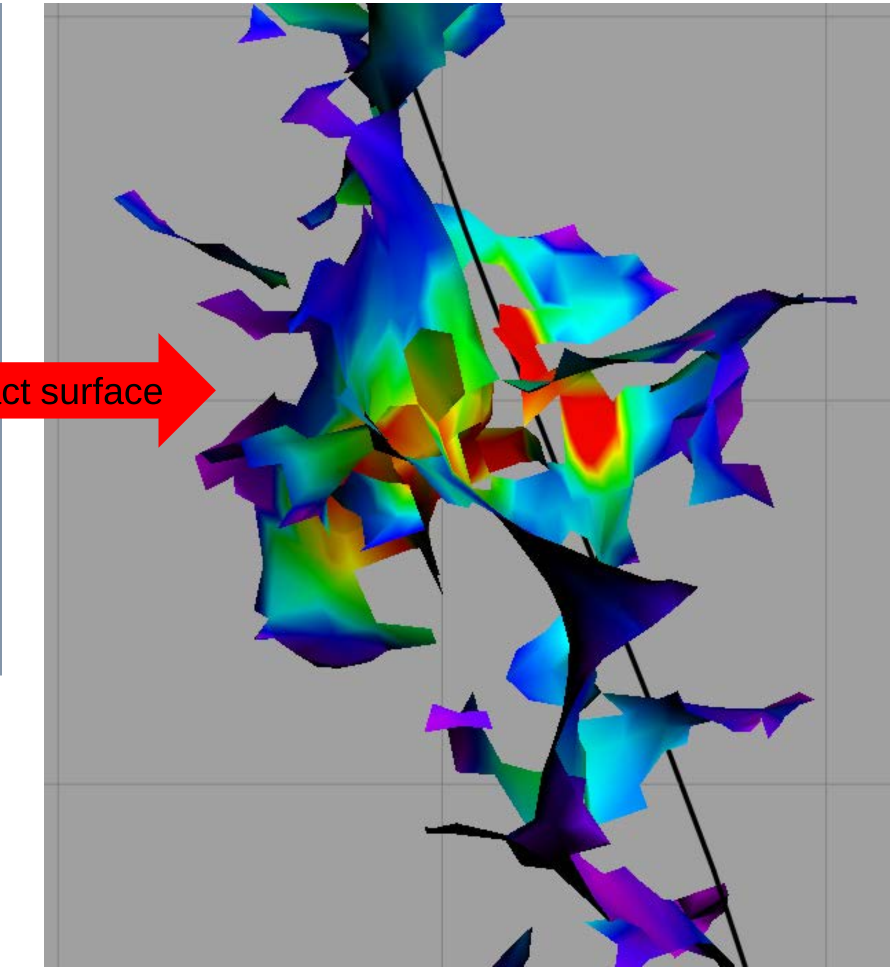
Semblance amplitude 相似值振幅

Raster TFIs can be exported as SEGY files.
光栅TFIS可以生成SEGY文件

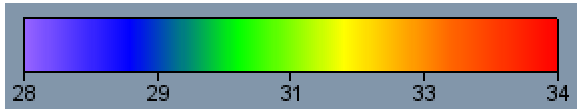
Generating a vector TFI from the stacked semblance volume

通过叠加的相似体产生矢量TFI





3D stacked volume



Semblance amplitude

Copeland, D.M., Lacazette, A., 2015, Fracture surface extraction and stress field estimation from three-dimensional microseismic data: URTeC 2155064, 19 p.

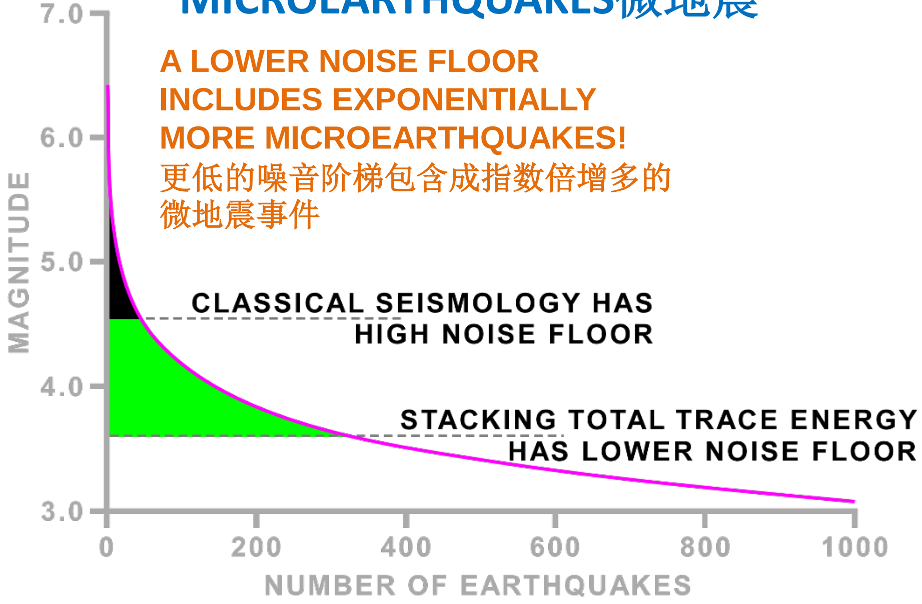
Vector TFIs矢量TFIs:

- are extracted directly from the semblance volume as ***tessellated surfaces*** – continuous surfaces composed of flat triangles that share edges,
- 由**tessellated 表面** 的相似体直接提取。***tessellated* 表面-** 由共享边的平面三角形组成的连续表面
- have no imprint of the processing grid geometry,
- 没有处理的网格印记
- can be exported as TSURF files – a standard, non-proprietary, widely-supported format,
- 可生成TSURF格式文件-标准的，无专利权的广泛的格式
- can be imported into 3D visualization and DFN modeling software.
- 可输入到三维可视化软件和DFN模拟软件

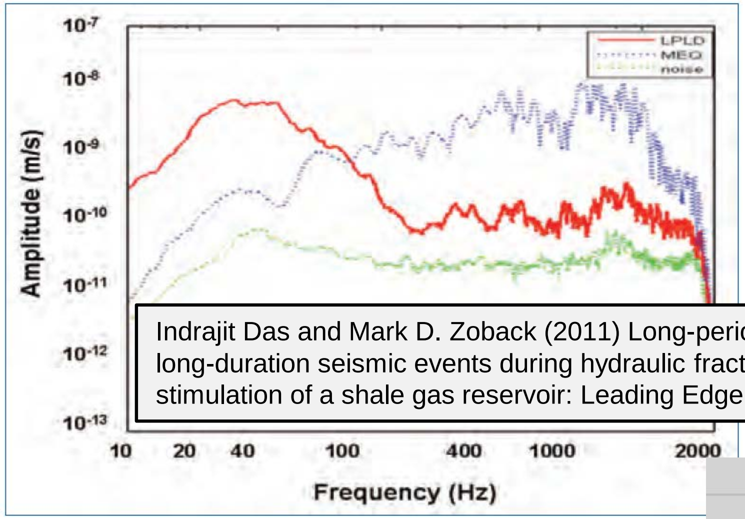
SENSITIVITY: IMAGING TOTAL TRACE ENERGY TAKES IN ORDERS OF MAGNITUDE MORE ENERGY THAN IMAGING ONLY MICROEARTQUAKES

敏感性：对所有的道集能量成像要比仅仅对微地震事件进行成像要多出很多数量级

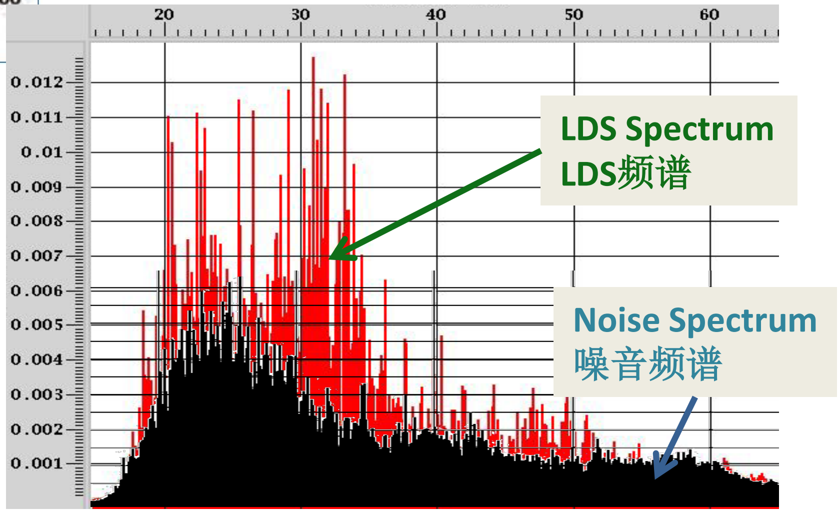
MICROEARTHQUAKES微地震



LPLD ENERGY长周期长持续时间能量



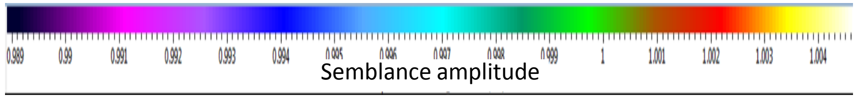
WATER/GAS HAMMERING

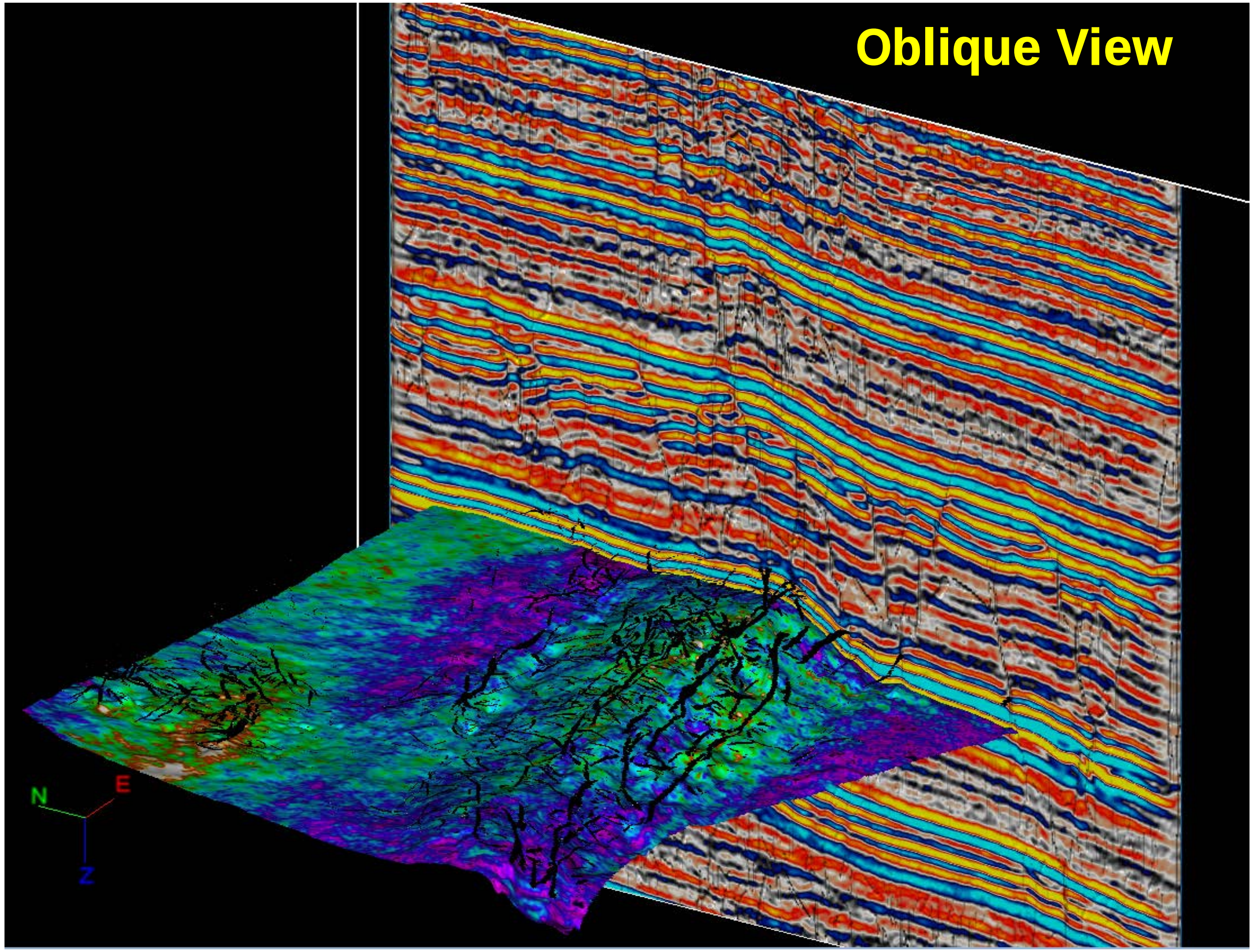


PRODUCTS

Before: Ambient imaging and fault probability
压裂前：周围环境成像和断层可能性

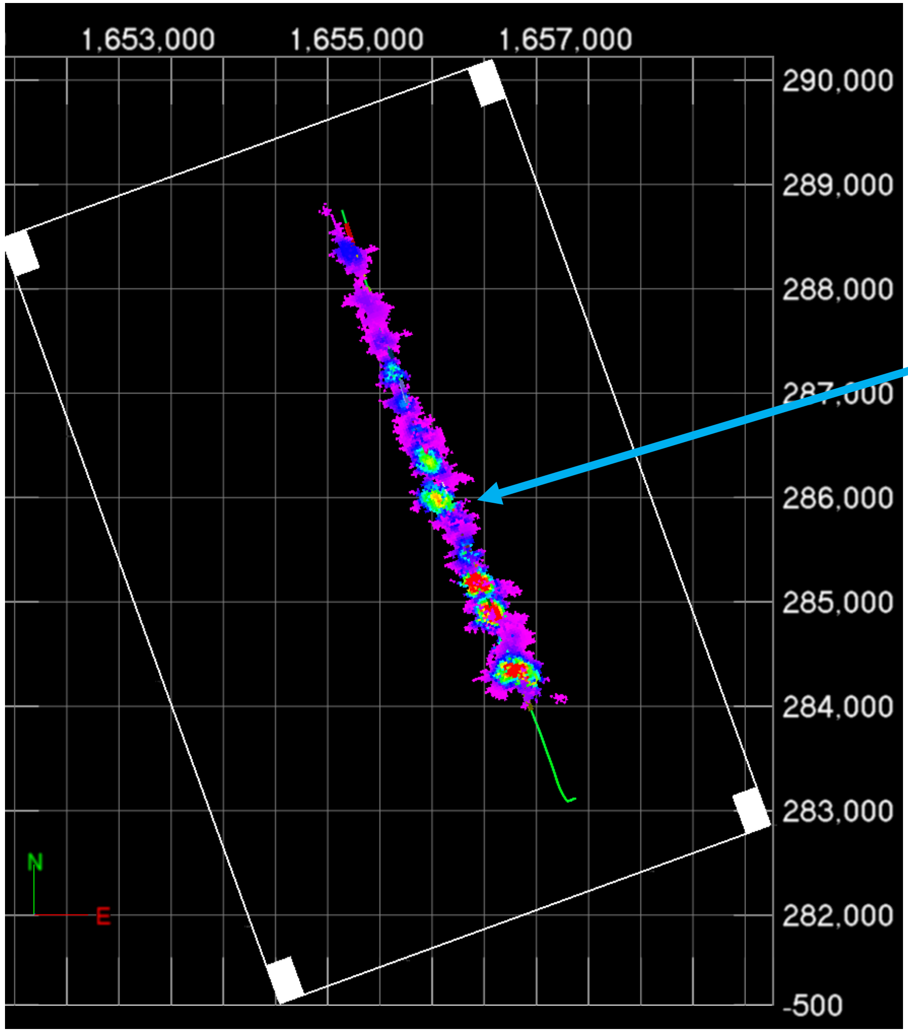
- **Seismic amplitude**
  地震振幅
- **Ambient emissions**
  周围环境
- **Fault probability**
  断层可能性



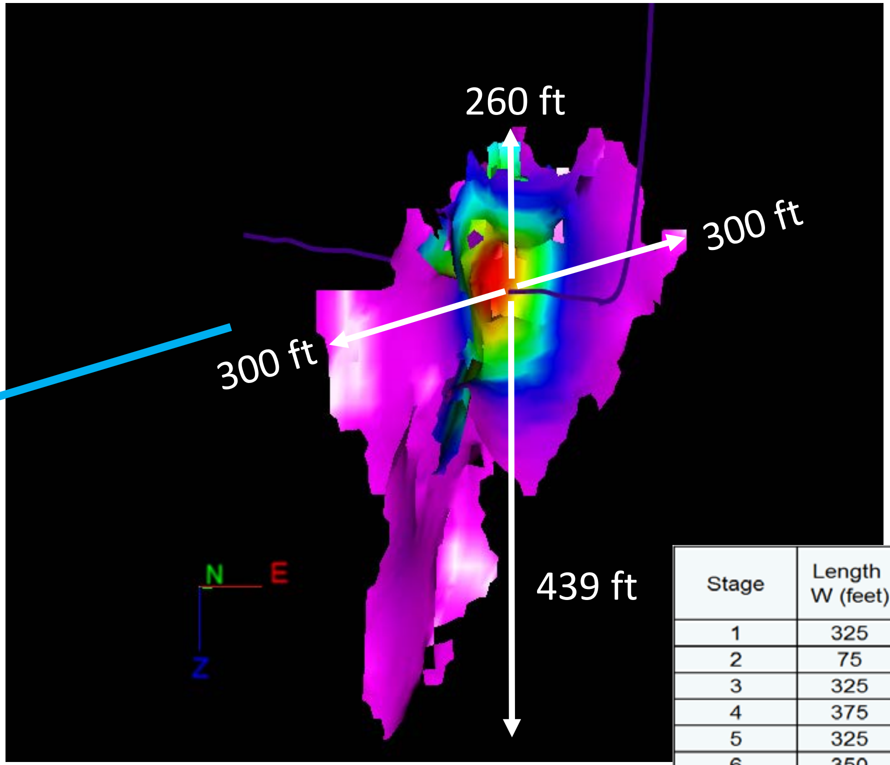


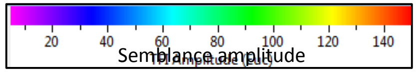
During: Induced fracture image TFI

压裂中：改造裂缝成像TFI



Near-well TFIs - Orthogonal projection viewed from above近井裂缝层析成像切片





fracture half-lengths & fracture heights
缝长和缝高

Induced fractures are either:

- **new fractures induced by the pumping, or**
- **pre-existing fractures or planes of weakness directly activated by the pumping.**

改造裂缝包括：

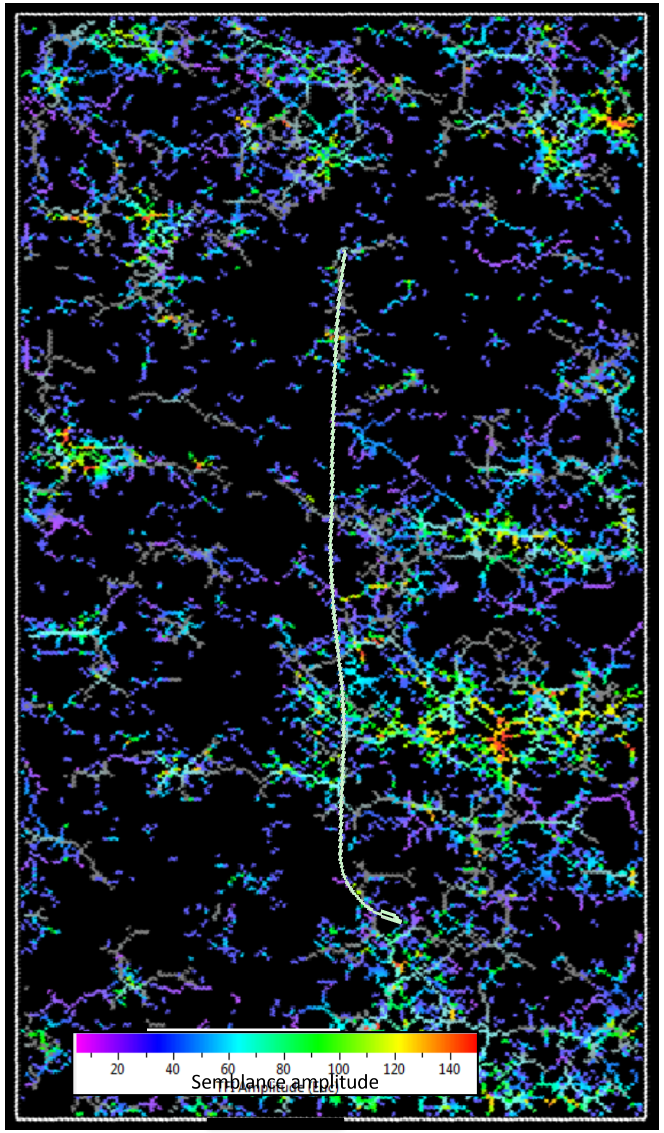
- 压裂产生的新的裂缝
- 压裂过程直接激活的已经存在的裂缝

Stage	Length W (feet)	Length E (feet)	Total Length (feet)	Height above well (feet)	Height below well (feet)	Total Height (feet)
1	325	125	450	285	89	375
2	75	0	75	135	39	175
3	325	0	325	260	214	475
4	375	75	450	285	289	575
5	325	150	475	210	589	800
6	350	0	350	160	114	275
7	325	125	450	260	214	475
8	325	225	550	310	439	750
9	425	125	550	285	264	550
10	300	150	450	235	164	400
11	300	125	425	285	414	700
12	300	300	600	260	439	700
13	325	275	600	260	314	575
14	250	225	475	235	489	725
15	425	350	775	335	664	1000
16	150	150	300	235	589	825
AVERAGE	306	150	456	252	333	586

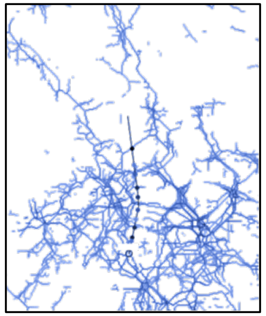
During: Reservoir-scale TFI

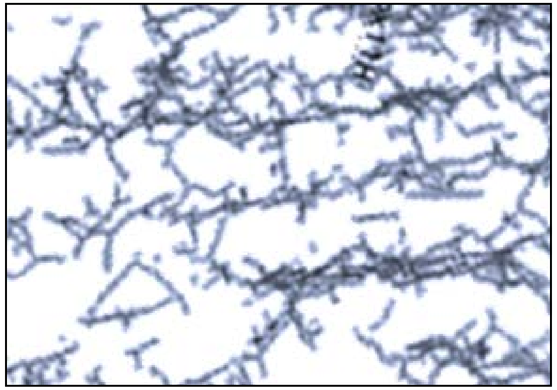
压裂中：储层范围TFI

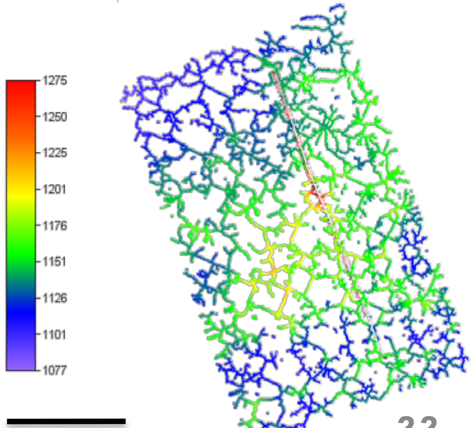
- Reservoir Scale TFI shows the macrofracture permeability field for the reservoir. 储层范围TFI显示储层渗透区域的微裂缝
    - Can aid in planning well locations and direction可以帮助规划井位和方向
- They are generally pre-existing fractures that produce microseismicity due to changes in fluid pressure and reservoir stress associated with pumping.
  他们通常是已经存在的裂缝，由于泵送过程中流体压力和储层应力的改变产生微地震。
- Some locations in the reservoir are highly fractured, some show little fracturing.
  储层中一些区域是高断裂区域一些是低断裂区域
- Horizontal slice at horizontal well depth
  水平切片深度为水平井深



1000 ft







2000 ft

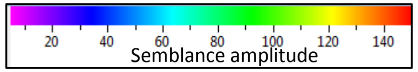
During: Reservoir-Scale Emissions

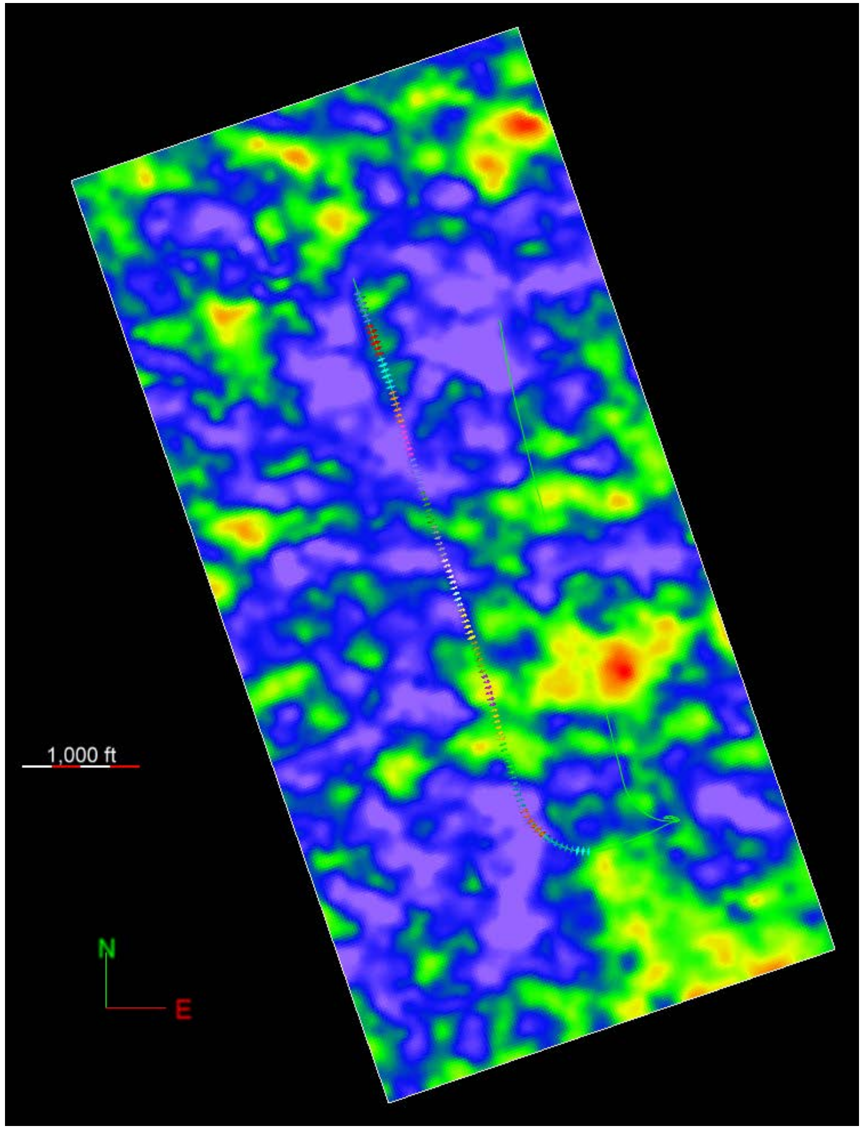
压裂过程中：储层范围微地震发射能量

- **Reservoir-scale microseismic emissions volumes show activity level through whole study volume**
- 储层范围微地震发射体积显示整个研究区域的活跃水平
- **Activity generally associated w/ pre-existing fractures that produce microseismicity due to changes in fluid pressure and reservoir stress associated w/ pumping**
- 活跃水平通常对应已经存在的裂缝，这些裂缝随着泵送由于流体压力和储层应力的改变产生微地震。
- **Some locations in reservoir highly active, some show very little activity**
- 储层中一些区域是高活跃区域一些事低活跃区域
- **Volume shows accumulation of total trace energy, incorporates all seismic activity, not just discrete microearthquakes**
- 体积显示了总道集能量的累积，叠加所有地震活动并非仅仅离散的微地震

- **Horizontal slice at horizontal well depth**

  水平切片深度为水平井深

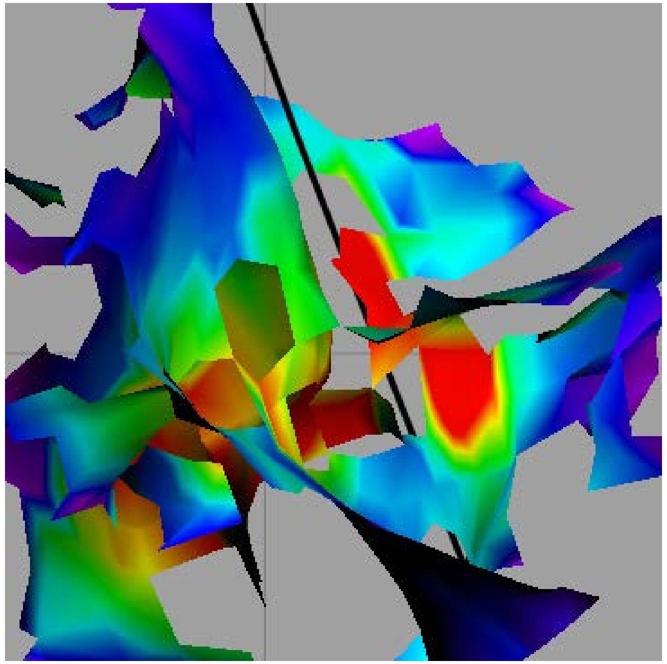




Before, During, After: Fracture orientation plots

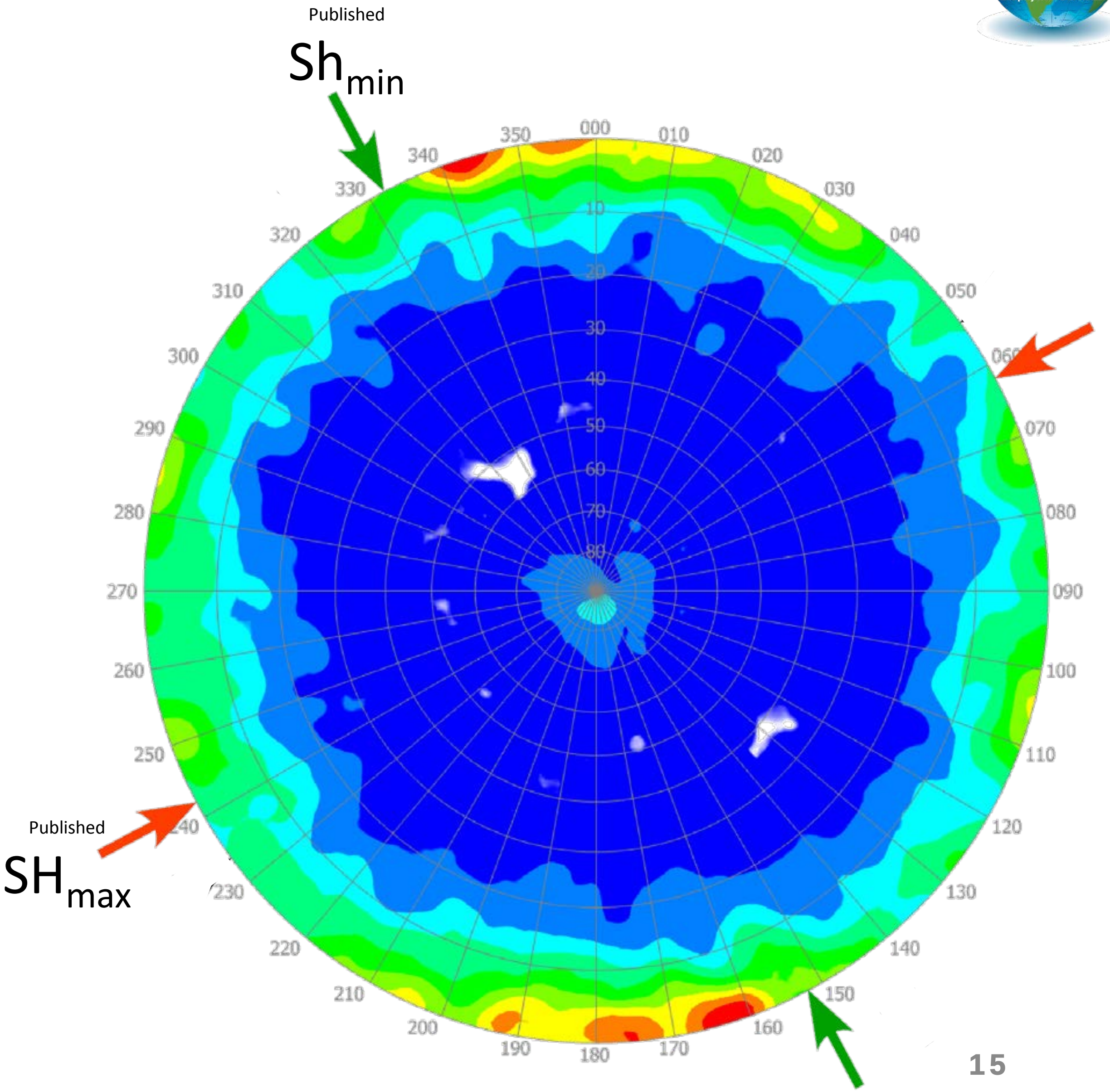
压裂前，中，后：裂缝方向图

- TFI are generated as tessellated surfaces
- TFI被生成为tessellated表面
- Contour poles to TFI facets, weighted for facet area
- TFI表面的极性等高线，表面积加权
- Lower hemisphere equal-angle projection for 14,966 facets 。14966个表面下半球等角度投影



Tessellated TFI

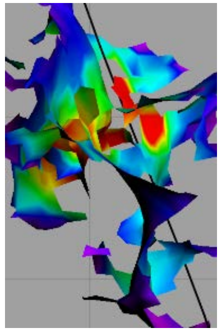
Detail showing facets

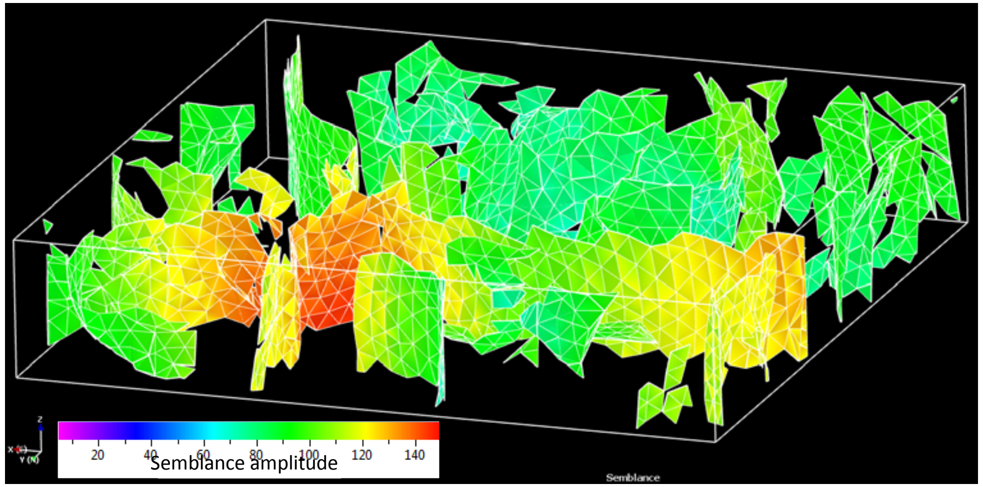


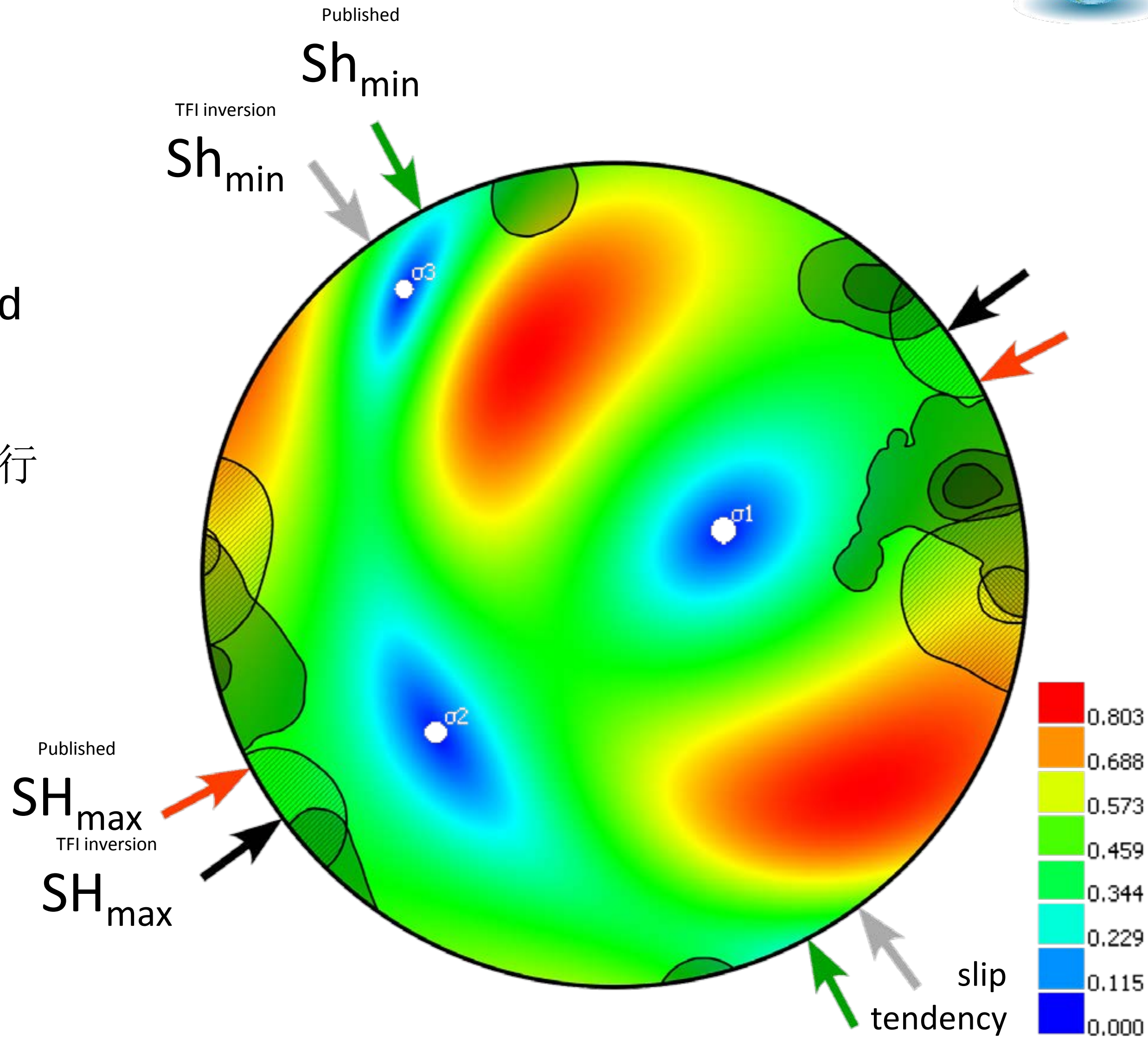
Before, During, After: Stress inversion

压裂前，中，后：应力反演

- TFI are generated as tessellated surfaces.
- TFI被生成为tessellated表面
- Slip Tendency Analysis uses the orientations, areas, and cumulative seismic activities of individual triangular facets of TFIs to find the orientations and relative magnitudes of the principal stresses that best fit the properties of the population of facets.
- 通过方向，面积和TFIs的个别三角面地震活性累积进行滑移倾向分析，用来确定主应力的方向和相对量级



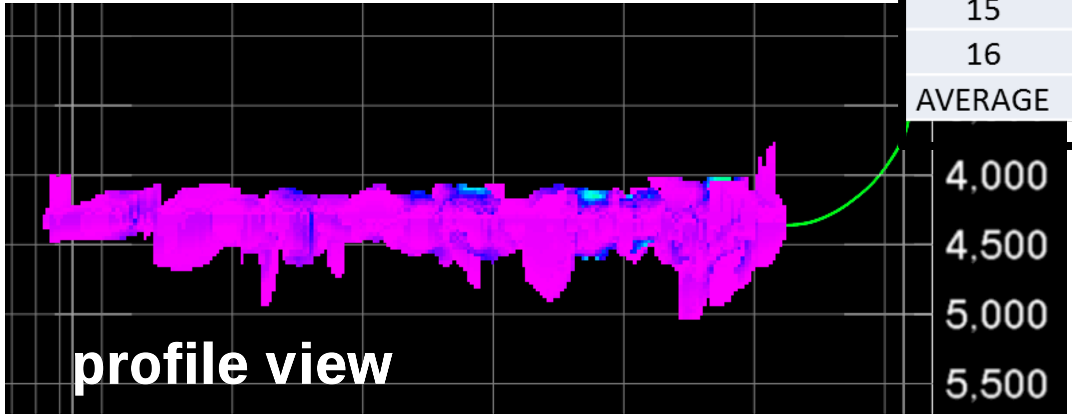


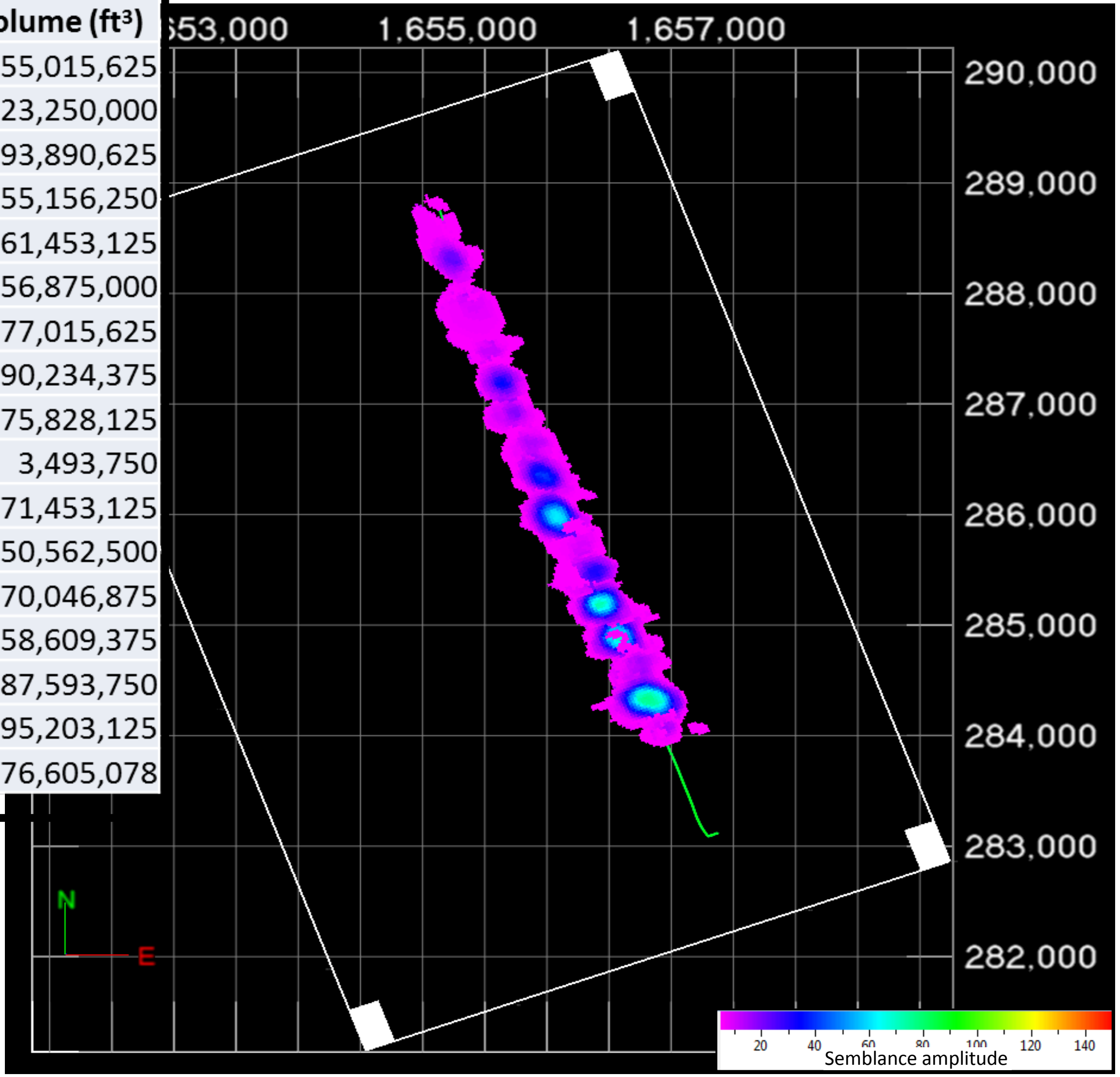


During: Stimulated Reservoir Volume (SRV)
压裂过程中：储层改造体积

- **Induced activity**
- 改造活动
- **Active-volume clouds directly connected to the stage being pumped**
- 能量云直接连接压裂中的压裂段
- **A better measure of SRV than a geobody derived from hypocenters**
- 比根据震源得到地质体更好的测量方法

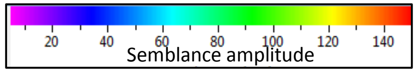
Stage	Volume (ft³)
1	55,015,625
2	23,250,000
3	93,890,625
4	55,156,250
5	61,453,125
6	56,875,000
7	77,015,625
8	90,234,375
9	75,828,125
10	3,493,750
11	71,453,125
12	150,562,500
13	70,046,875
14	58,609,375
15	187,593,750
16	95,203,125
AVERAGE	76,605,078

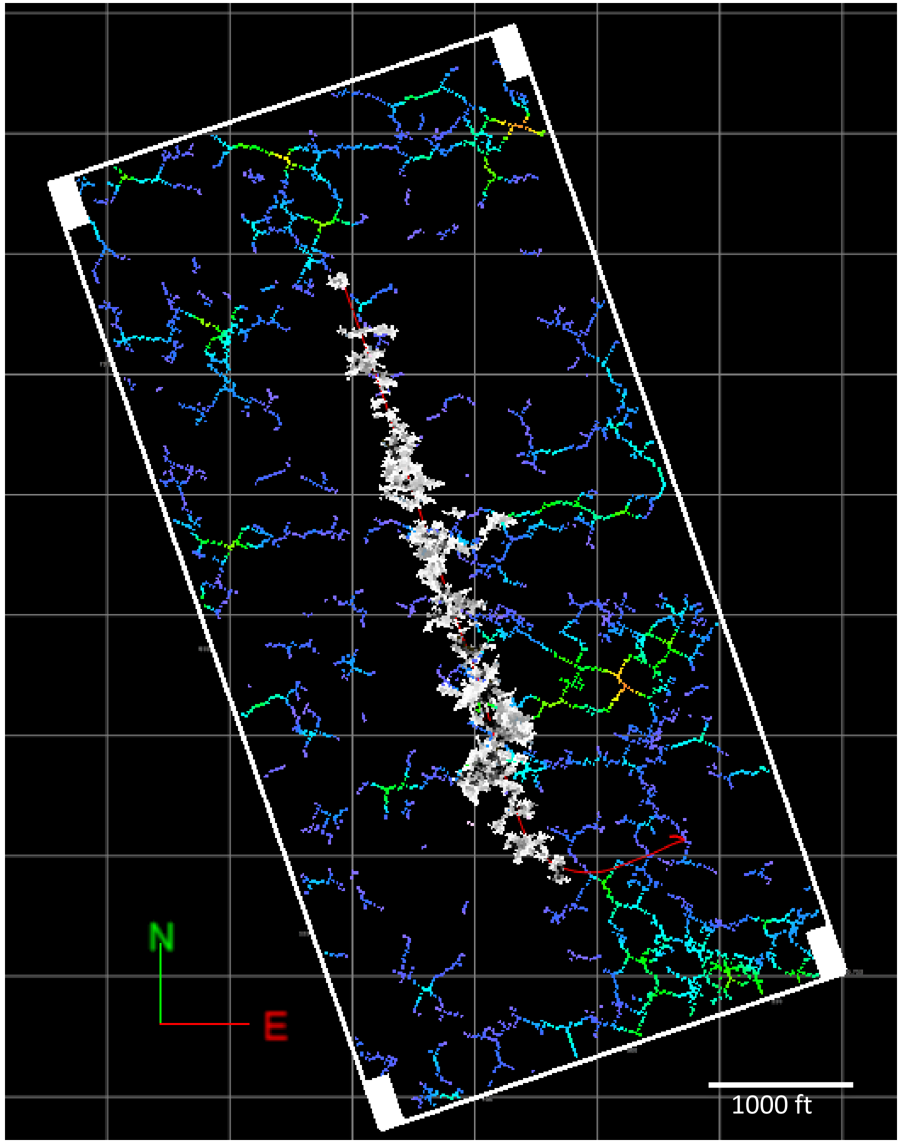




During: Reservoir-Scale TFI & Induced TFI
压裂过程中：储层范围TFI和压裂改造TFI

- **Viewing the reservoir-scale and induced TFIs together shows how the induced fractures interact with the transmissive fractures within the reservoir.**
- 储层范围和压裂改造TFI显示了压裂改造裂缝和传导裂缝之间的相互作用
- **RS TFI shown as a horizontal slice at horizontal well depth**
- 储层范围TFI水平切片深度为水平井深
- **Induced TFI shown as a projection of a 3D volume**
- 压裂改造TFI为三维立体投影

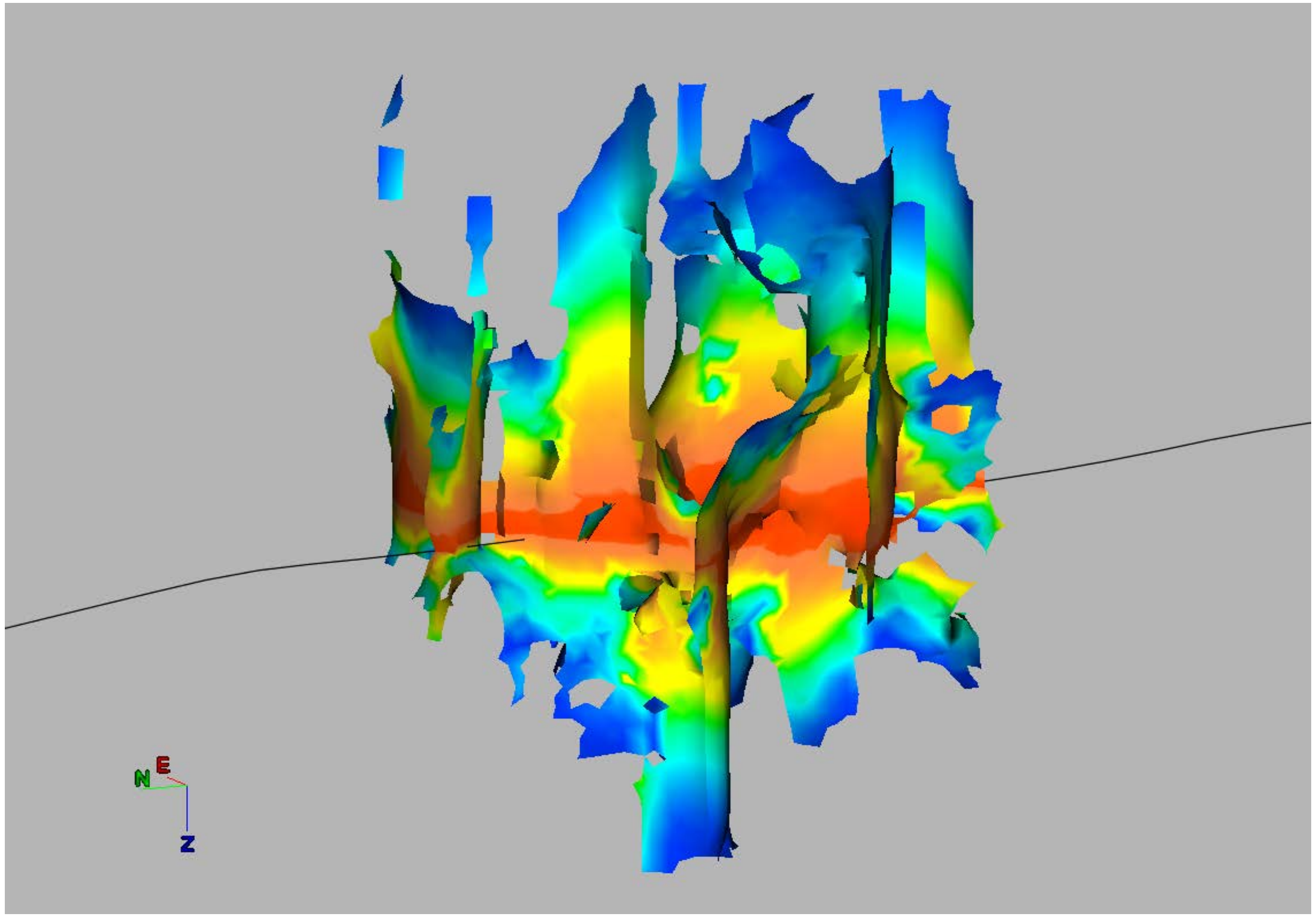


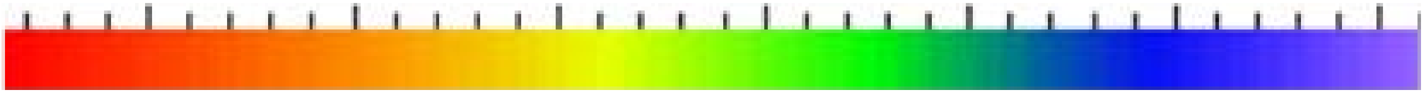


During: Fracture propagation mapping 压裂过程中：裂缝延伸图

Tomographic Fracture Image^{SM} (TFI) colored by activation time

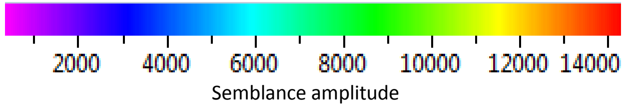
根据活动时间由颜色显示裂缝层析成像^{SM} （TFI）

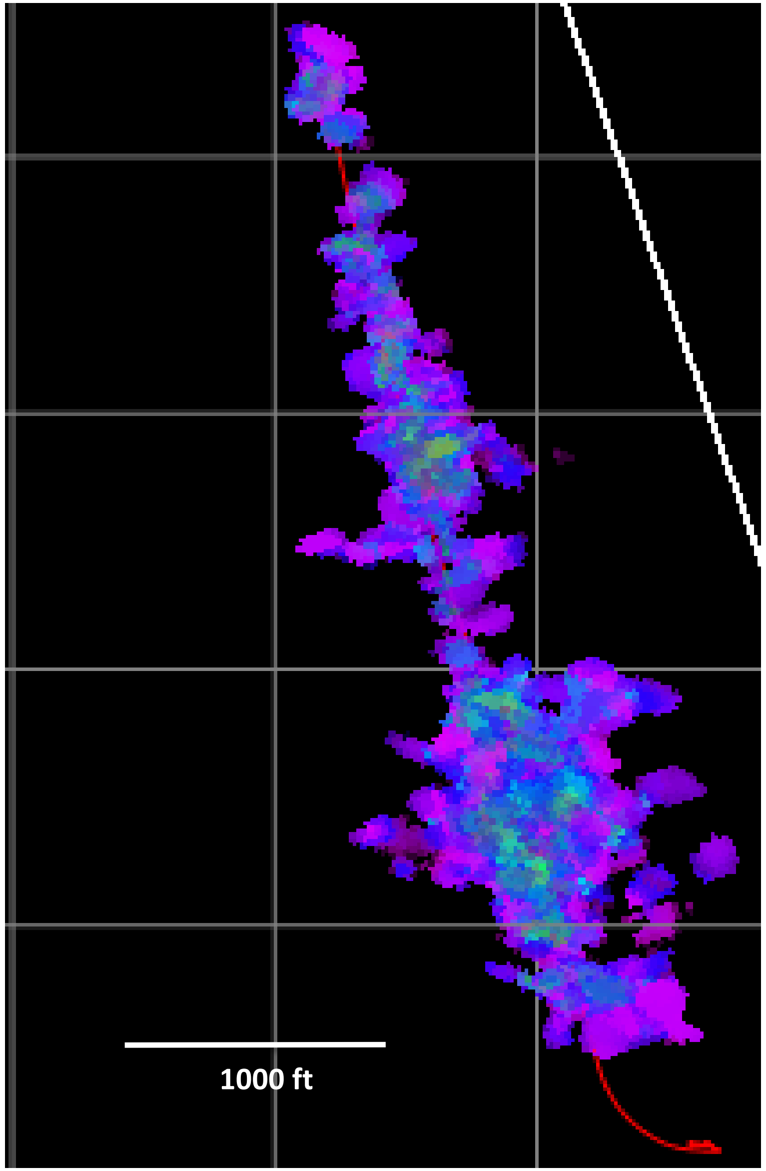




After: Active Production Volume (APV)
压裂后：成产活跃体积

- SRV is measured during hydraulic fracture completion.
- 水力压裂过程中测量储层改造体积
- Some of these active fractures close as fluid pressures decline.
- 活动裂缝的一部分随着流体压力的下降产生
- Monitoring during production shows only locations activated by the production activity.
- 生产开发过程的监测显示开发过程中的活动位置
- The APV is smaller than the SRV.
- 生产开发活跃体积要小于储层改造体积

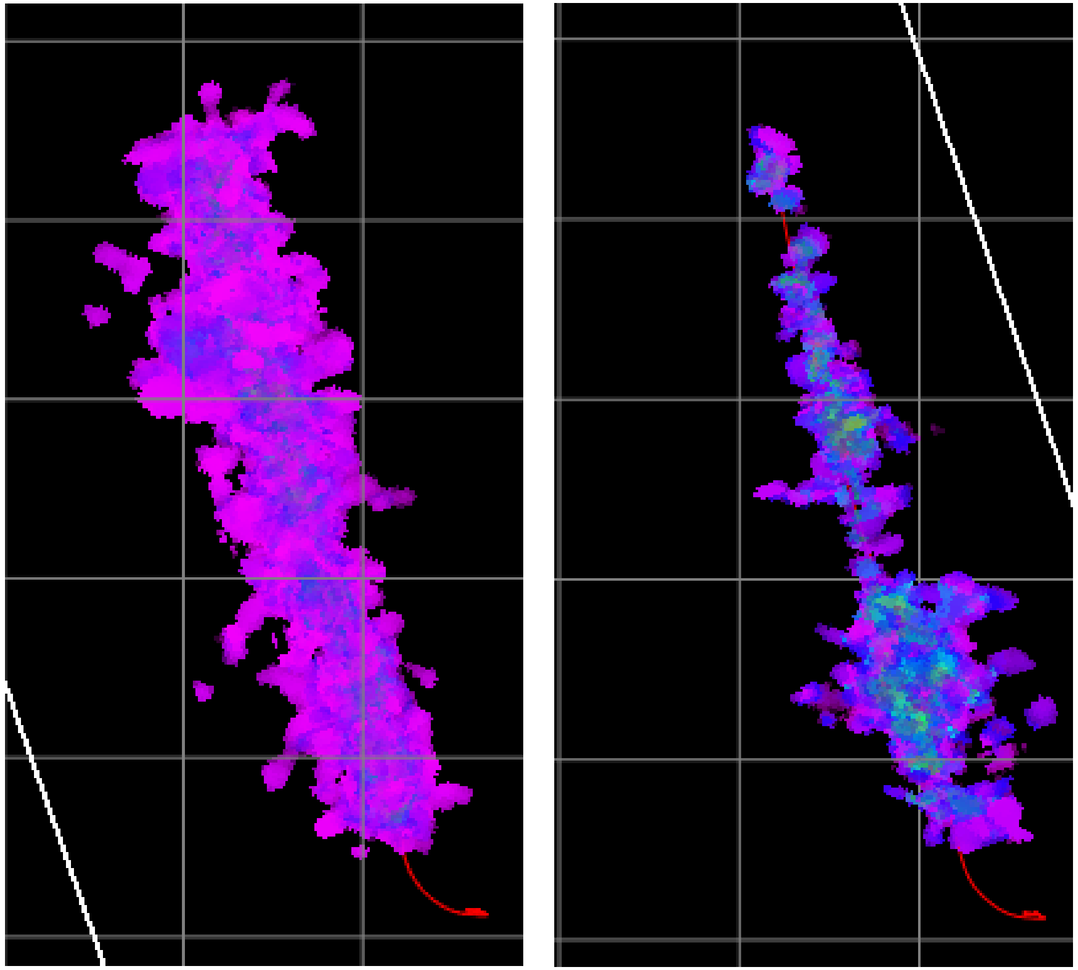




After: SRV vs. APV Comparison

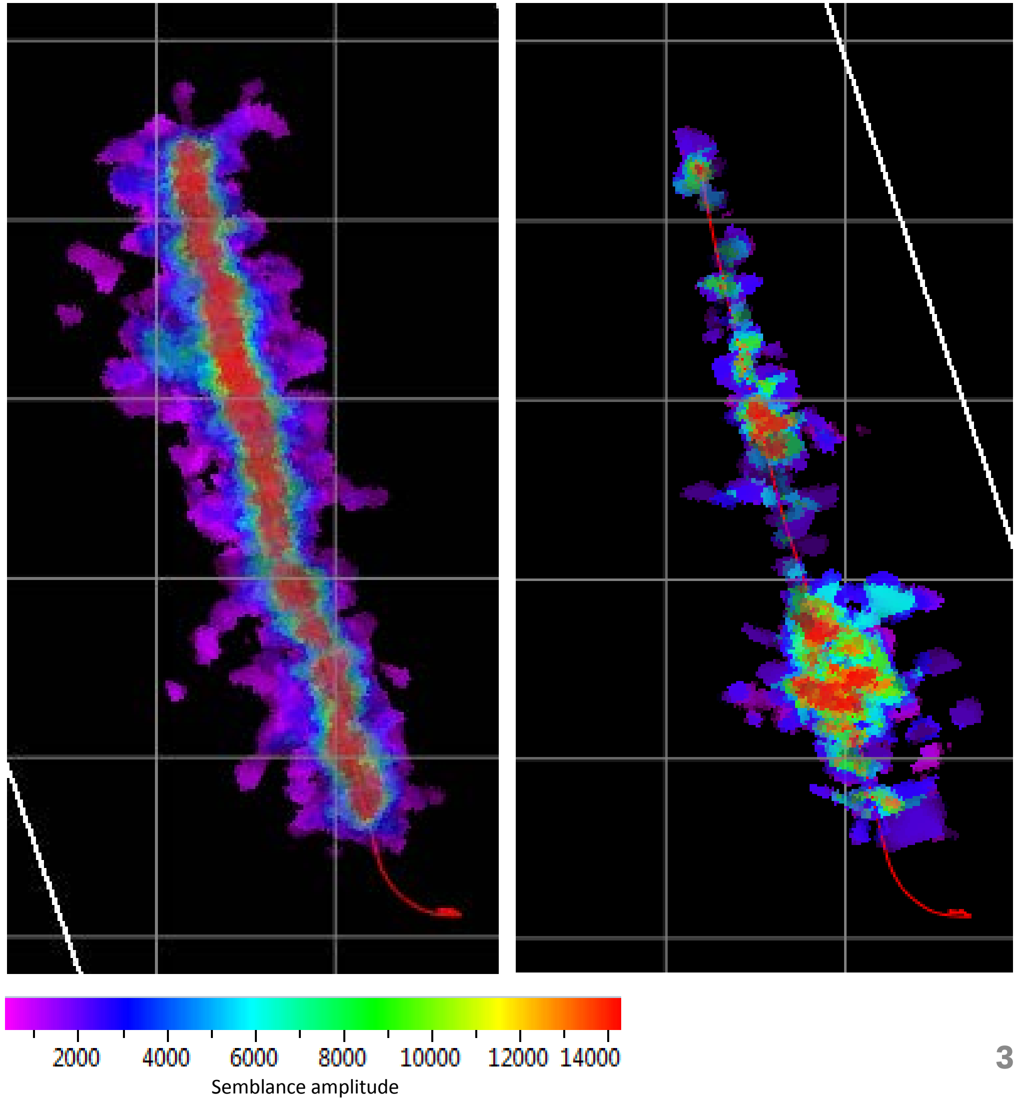
压裂后：SRV和APV对比

Top view - full volume
顶视图-全体积

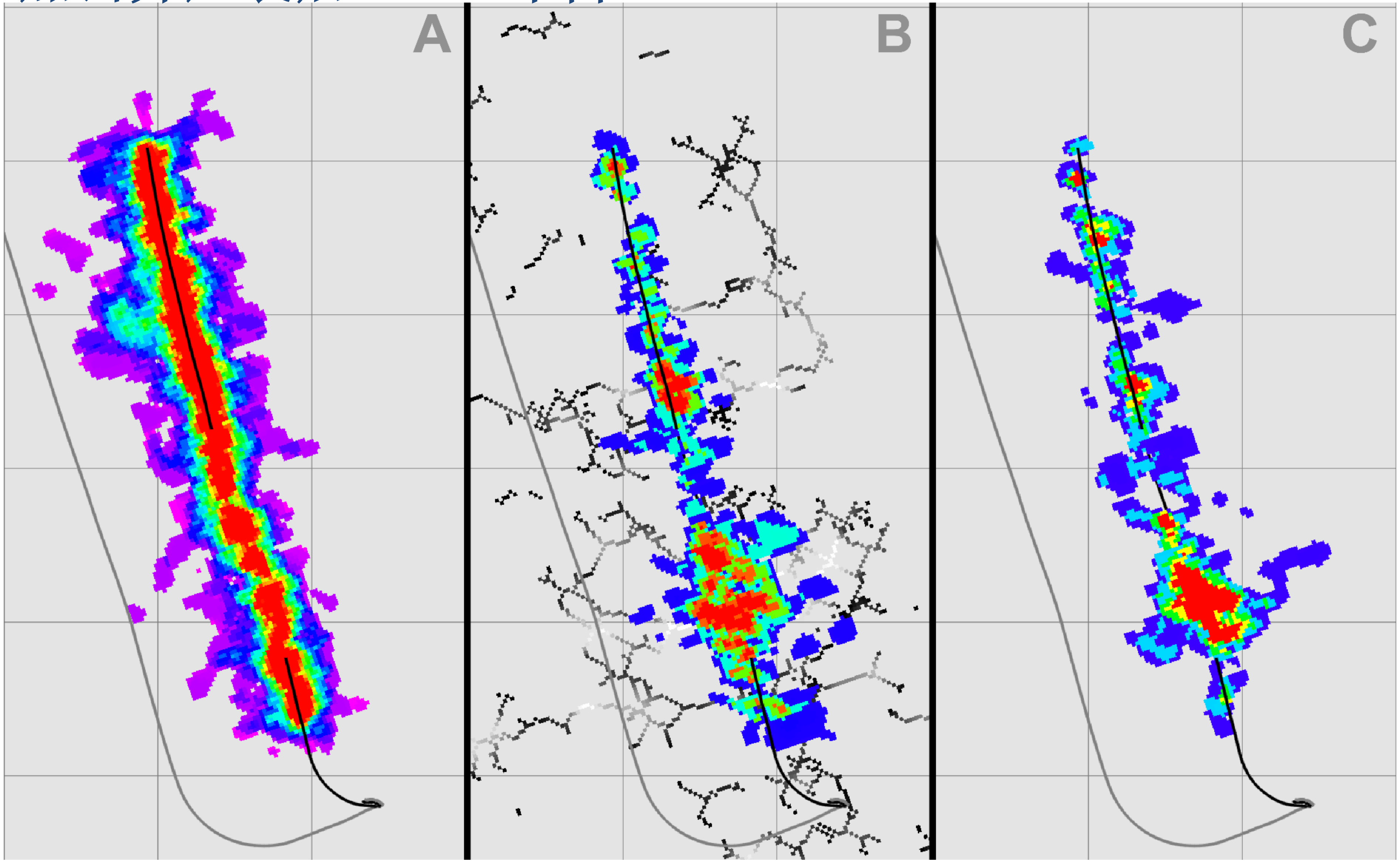


SRV Volume = 2,181,031,250 ft^3
APV Volume = 1,390,625,000 ft^3

Horizontal slice along well path
延井轨迹水平切片



After: APV decrease after frac of adjacent well
压裂后：加密井压裂后，APV下降

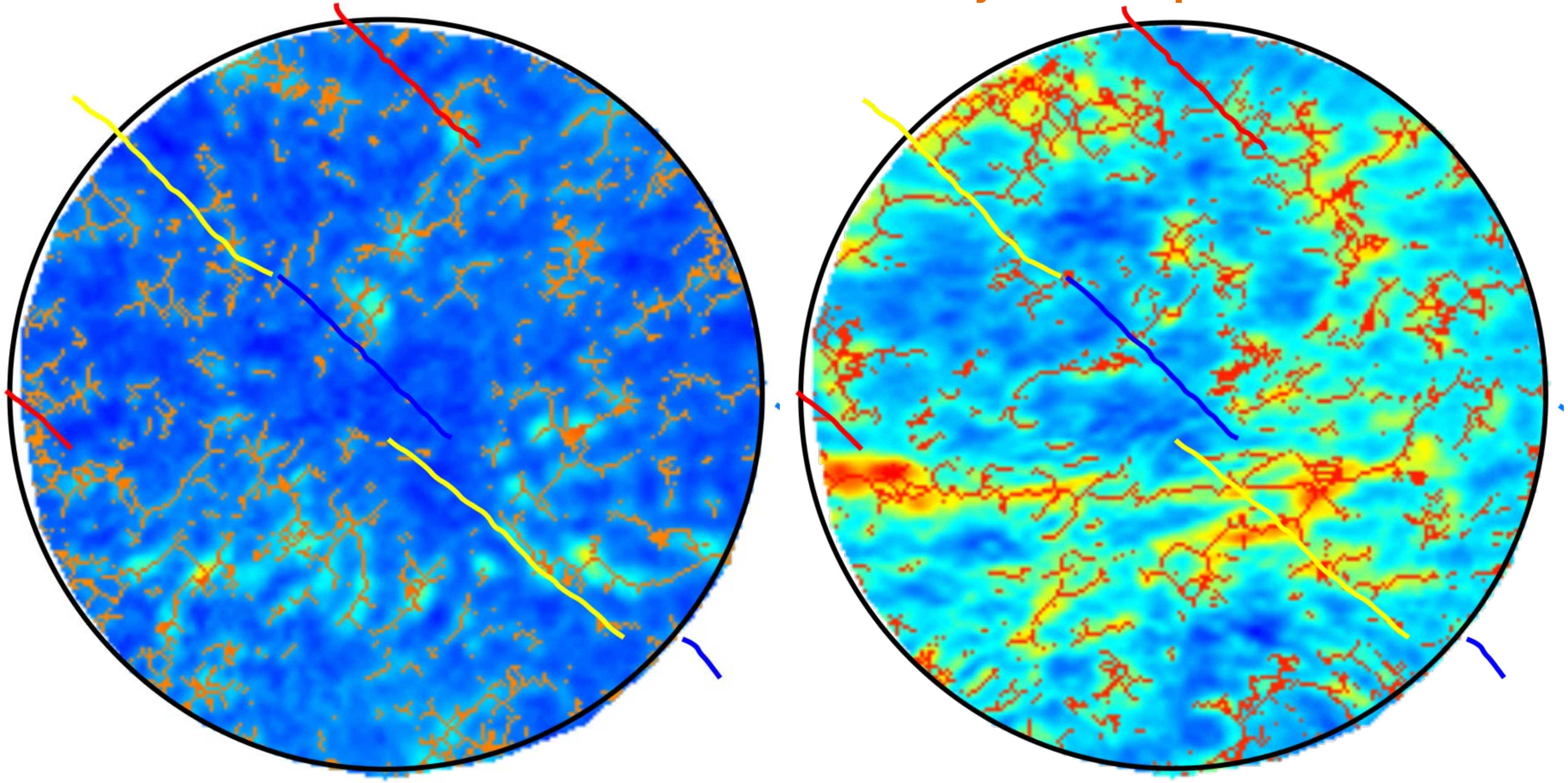


EOR MONITORING
提高采收率监测

DEPTH SLICES – TFI ON STACKED SEMBLANCE
WATERFLOOD, SANDSTONE RESERVOIR, CANADA, DEPTH ≈ 2km
深度切片-TFI覆盖在叠加的相似值上

No injection, no production

Injection + production



Circle diameter = 3,350 m / 11,000 ft

TFIs CAN BE USED DIRECTLY FOR DISCRETE FRACTURE NETWORK (DFN) RESERVOIR SIMULATION AND CAN BE IMPORTED DIRECTLY INTO DFN SIMULATORS

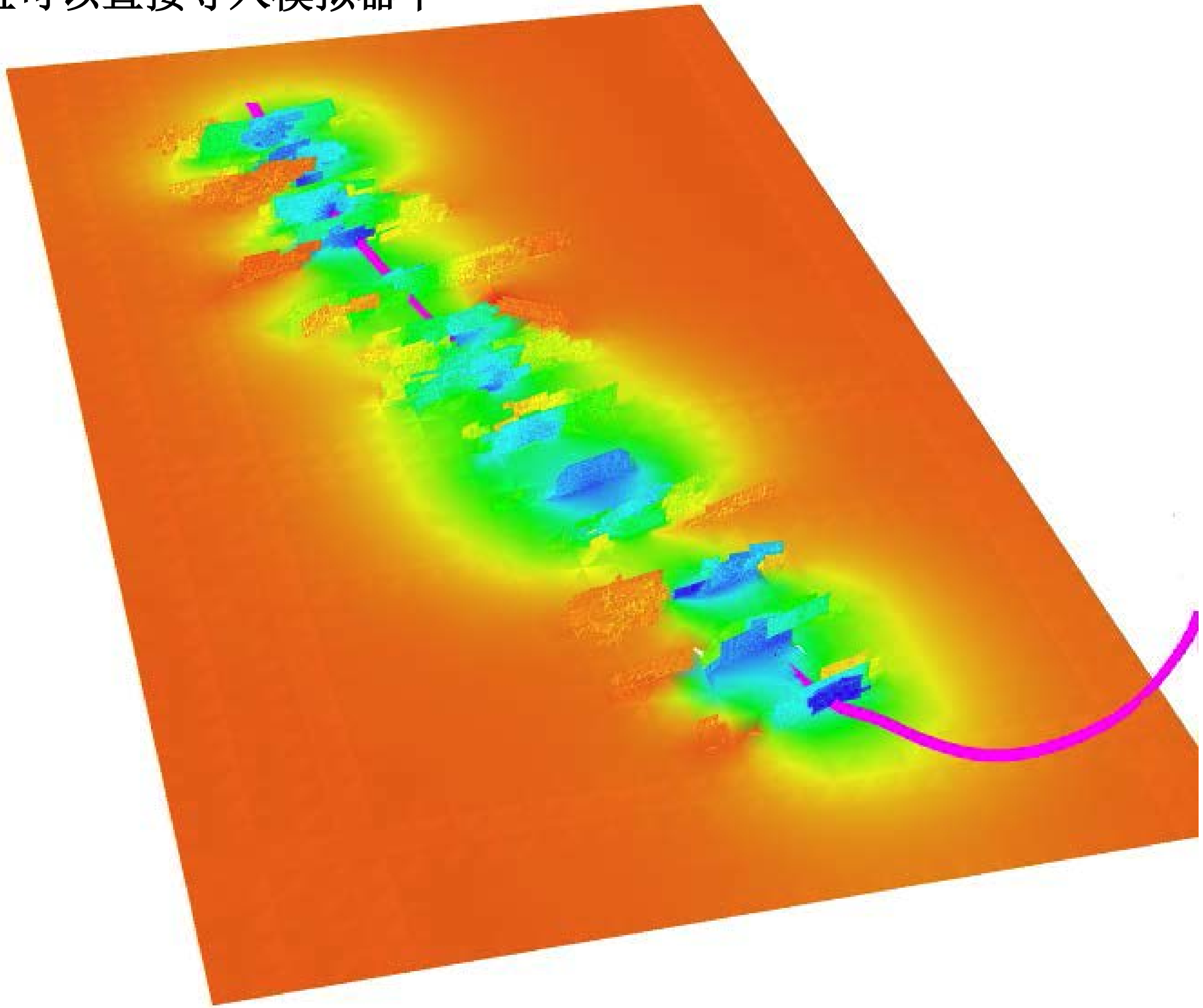
TFIs可以直接用于离散裂缝网格（DFN)储层模拟，并且可以直接导入模拟器中

Pressure snapshot of single-well simulation

单井模拟压力快照

Pressure snapshot during DFN simulation of production. 3-D surfaces show hydraulic fractures simulated with DFN model conditioned to TFI data. These are embedded in a semitransparent depth slice of the matrix pressure. Colors indicate pressure. The limit of departure of reservoir pressure from the virgin reservoir pressure defines the Tributary Drainage Volume up to the specified time.

生产中的**DFN**模拟压力快照。三维表面显示由**TFI**数据限制的**DFN**模型的水力压裂模拟。这些嵌入一个半透明的压力基质深度切片。颜色代表压力。来自于原始储层应力的储层应力偏差限制确定了支流排水体积。



Lacazette, A., Dershowitz, W., Vermilye, J., 2014, Geomechanical and flow simulation of hydraulic fractures using high-resolution passive seismic images: URTeC 1935902, 10 p.

FRAC HIT – MARCELLUS FM., PENNSYLVANIA

The following movie shows a frac hit from a horizontal well onto an old vertical producer. The vertical well was equipped with a pressure and chemical tracer monitor. The movie shows stage 3. The TFI connecting the two wells developed almost immediately when stage 3 began. The activity resulted from increasing the pressure and hence decreasing friction in a preexisting fracture zone allowing release of stored elastic strain energy. However, the pressure and chemical tracer were not detected until the onset of stage 5. Two stages of pumping may have been required to pressurize the fracture system. Another reason may be the connection of the fracture zone to stage 5 that is clearly visible in the stage 3 TFI.
接下来的电影显示压裂击穿从一个水平井到一个旧的垂直井。垂直井放有压力计和化学示踪剂。电影描述了第三段的情况。当第三段开始压裂，两口井之间裂缝直接相连。这种结果是由于已存在的断裂区域的压力增加和摩擦减少，该区域使允许弹性应变能量的释放。然而，压力计和化学示踪剂直到第五段才发现这个情况。两段的泵送可能已经要求对裂缝系统进行加压。另一个原因可能是裂缝与第五段相连，这点在第三段TFI中清晰体现。

A new approach to Microseismic Monitoring
微地震监测的一个新趋势

Before - During – After

压裂前-中-后

During - Image the effect of stimulation. **Map interactions between wells.**

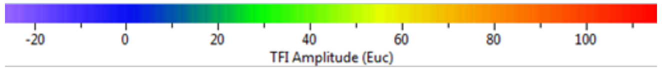
压裂中-改造效果成像。井间图像交互

Data Driven Products

Products are computed directly from the recorded data. Products provided by other service contractors are derived based on hypocenters and MEQs. For these products, a model of the Earth is assumed and the parameters for the model are estimated from the hypocenter results.

数据驱动产品

产品通过记录的数据直接计算。由其他服务商提供的产品只是基于震源和微地震事件。对于这些产品，需要假定地质模型并且模型参数由震源结果评估。



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THANK YOU 谢 谢

QUESTIONS? 有 问 题 吗 ？