Modelling of Fractures Developed Due to Structural Deformation in the Karjan Prospect of Cambay Basin in India*

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Search and Discovery Article #41090 (2012)*
Posted November 30, 2012

*Adapted from extended abstract prepared in conjunction with oral presentation at GEO-India, Greater Noida, New Delhi, India, January 12-14, 2011, AAPG©2012

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Abstract

The unconventional fractured basalt reservoir of the Karjan prospect in Cambay basin has proven to be a promising oil play in the area. Recent oil finds in trap basalts in the Karjan prospect, Cambay basin India, are an immediate motivation to understand the occurrence of oil and the role of fracture distribution. This paper describes the method adopted to characterize the discrete fracture systems within the basalt for hydrocarbon accumulation as an unconventional trap.

The seismic data used to map the top of the trap surface and a reflector below the surface guided by the events with varying continuity to generate a volume of trap strata in the Karjan prospect. This volume is utilized for forward modelling to analyze deformation attributes, using geo-metric and geo-mechanical restoration workflows of structural modelling software.

From the mapping of faults, we found that the area has undergone tectonic stresses in two directions. This has defined a number of fracture sets.

The restoration process calculates stress and strain attributes. These attributes are used for fracture modelling to define two sets; this has worked as a dip and azimuth constraint for 3D Discrete Fracture Network (DFN) of defined fracture sets. The paper analyzes and presents the result of fracture modelling. The workflow used for fracture modelling can be used by petroleum industry to define spacing, density and orientation of the various fracture systems. The optimal modelling results will depend upon appropriateness of geometries adopted for restoration and constraining parameter of fracture systems. The discreet fracture network model generated is a direct input for Simulation Model for further study and to generate the field development model.

Introduction

The natural fractures play an important role especially in low-permeability tight rocks having virtually no primary porosity. As fracture do provide the required secondary porosity and permeability for oil entrapment within tight rocks. Precisely for this reason, many workers have attempted to determine the characteristics of fractures. These workers have adopted mainly geophysical methods in form of P-wave and shear wave analysis (Mueller, 1992) or cross-hole tomography as reliable indicators of fracture orientation and distribution (Satio and Ohtomo, 1989). Gerard Bloch (2003) expressed seismic facies analysis as a powerful tool for fracture detection. Chang and Gardner (1993) suggested that the fracture orientation of a subsurface fracture zone may be determined by analyzing P-wave interval velocities. Fractured zones can be indirectly predicted by means of seismic inversion detecting lithology distribution (Jun Chen et al, 1999).

The P-wave can also be used for fracture detection by characterizing presence of low stacking velocities, anisotropy and seismic wave attenuation. Beside these geophysical methods, Mai Thanh Tan (2001) suggested that the highly fractured nature of basement reservoirs is created during the process of tectonic deformation, cooling, hydrothermal and weathering. Role of structural deformation in development of natural fractures is demonstrated by Sanders and Murray (2001) using structural modelling to characterize fractured basement reservoirs and concluded that any deformation process can potentially be modeled and analyzed in 3D Move. 3D Move is a structural modelling software from Midland Valley Exploration Ltd. (MVE) that primarily uses geometric restoration as a modelling process.

However, MVE has developed advanced 3D structural modelling software known as 4DMove. The 4DMove software has a 4DMove Restoration module. This module has an exclusive algorithm - The Mass spring Restoration. This is a Geo-mechanical restoring of volumes and surfaces in comparison to geometric restoration by 3D move restoration techniques (fault and fold restoration). 4D Restore creates the geo-cellular grids with strain outputs that can be directly export to fracture modelling module 4D Frac of 4DMove.

The present study demonstrates the modelling of fractures developed due to structural deformation in the Karjan prospect of Cambay basin by using 4DMove software. The paper discusses the workflow used in fracture modelling and analyze the results obtained thereof.

Area of Study

The Padra-Karjan area, located on the eastern rising flank of Broach block in Cambay Basin (Figure 1), is distinctive as an unconventional fractured basalt reservoir and has proven to have promising oil plays besides Tertiary sediments. The area of Karjan Prospect was selected for fracture modelling based on seismic attributes of Karjan 3D volume (Figure 2) that suggests the presence of extensional fractures due to structural deformation in the area.

Objectives

The objectives of the present study are:

- To generate Discrete Fracture Network;
- To evaluate capability and utility in predicting the discrete fracture network for reservoir simulation;
- To understand the limitations and constraints.

Workflow

Methodology includes creation of geo-cellular volumes by mapping the present day top and bottom surface of geological strata to generate DFN's generated using 3D seismic data. Identifying seismic reflectors within low permeability rocks like trap basalt and granite is difficult on seismic data. The alternative is to generate mathematical geo-cellular volume by using surface top and adding layers of constant thickness to it. However in the present study, we attempt to map the bottom of the geo-cellular volume following a seismic event (may be corresponding to the bottom of fractured/weathered basalt layer) of varying continuity below trap top surface on seismic data (Figure 3) to create a real geological dataset.

This volume is utilized as a present day geological structure to generate a Discrete Fracture Network as follows:

- Step 1: Present day model is restored using geometric/Geo-mechanical Restoration. The results represent the geological situation before deformation took place. At this stage, the fracture growth is simulated using constant spacing and orientation.
- Step 2: The restored geological situation is forward modelled to simulate the present day structure. Strain estimates are calculated during the simulation.
- Step 3: stress and strain in the above process is represented by colour mapping of surface.
- Step4: Shear fracture growth is simulated in fracture modelling module 4DFrac of 4DMove using the strain parameters obtained during restoration process.
- Step5: From the mapping of faults, we found that area has undergone tectonic stress in two directions. This has defined number of fracture sets. Therefore, defined two fracture sets with orientation constrained by dip and azimuth parameters of faults mapped.
- Step 6: Generate Discrete Fracture Network (DFN), perform connectivity analysis and output the volumetric (porosity, sigma etc.) and directional (permeability) properties.
- Step7: Modelled output saved to export for simulation studies.

Procedure and Result

A seismic horizon mapped near to the top of Trap basalt surface and a seismic event below as shown in Figure 3 and exported to 4DMove software. 3DMove software used to create two grid surfaces one for trap-top and another one for a surface within trap basalt to generate a Geo-volume (Figure 4) using Volume creation tool. We used this Geo-volume as input to create a geo-cellular grid volume in 4DMove required for fracture modelling in 4Dfrac module. Present day structures can be restored to the initial surface by using either geometric restoration in3DMove or Geo-mechanical

(Mass-spring) restoration in 4DRestoration module of 4DMove. Both restores the present day structure to the initial modelled surface i.e., flat (Figure 5). Here, we assume that the initial surface was flat and, subsequently due to tectonic stress, it deformed to the present day structure.

This flattened surface is the input for forward modelling to deform it to the present day structure using the geometric (folding) or geo-mechanical (virtual mass spring) kinematic algorithm. Both of these methods store the change in the stress/strain attribute due to restoration mechanisms. Figure 6 shows the major stress/strain distribution as a colour-coded surface. The surface grid stores the strain and stress parameters, therefore restoration can be done for intermediate stages also and resultant attributes can be analyzed. Analysis does provide valuable insight to the geologists about deformation processes involved.

Volume restoration may be preferred over than surface restoration; however, in this study surface restoration is used for mapping of events below the trap basalt surface and is not reliable due to seismic resolution. The volume is used only to create the geo-cellular volume grid for 3D discrete fracture network distribution in fracture modelling process.

In the 4D Move, you can create as many DFN as you like. However, the choice is normally restricted through analysis of fracture data from the well. If well data has fracture parameters it can be analyzed in 4D Move to provide two important parameters: one is mean principal direction (Dip/Azimuth) and another is Fisher Dispersion, (k). These two parameters are used to constrain the DFN's. In the case where fracture data is not available from the well, the same information can be obtained from field analogues or through forward modelling.

In the present study, we define two fracture sets (4DFrac_0 and 4DFrac_1). Orientation analysis of faults mapped in the area suggests the area has undergone tectonic stress in two directions viz., Dip/Azimuth of 63°/267° and 71°/203°. Input parameters for these two fracture set is given in Table 1. These parameters are used to generate two DFN's shown in Figure 7. These two DFN's are analyzed for component connectivity as shown in Figure 8 with and without Geo-volume. For better visualization and analysis, they are also superimposed on surface topography and grid (Figure 9). The connectivity analysis of the DFN's is given in Table 2.

The connected DFN component is used to drive the reservoir parameters like degree of connectivity, permeability and porosity. The spatial distribution of these parameters is shown in Figure 10.

Conclusion

Forward modelling recreates the historical deformation and consequently the changes in stress and strain attributes. These attributes are attached with restored surface grid and can be analyzed for different stages of restoration and compared. These attribute changes can be used in fracture modelling processes as constraints for fracture distribution and computation of reservoir parameters. Distribution of reservoir parameters of 3D DFN can be analyzed to identify the fracture/secondary reservoir porosity areas for locations of exploratory drilling. The output can be directly used for reservoir simulation process. However, its geological validity depends upon the appropriateness of restoration mechanisms and constraining parameters of fracture sets. Moreover, use of volume restoration instead of surface restoration may lead to more geological plausible results.

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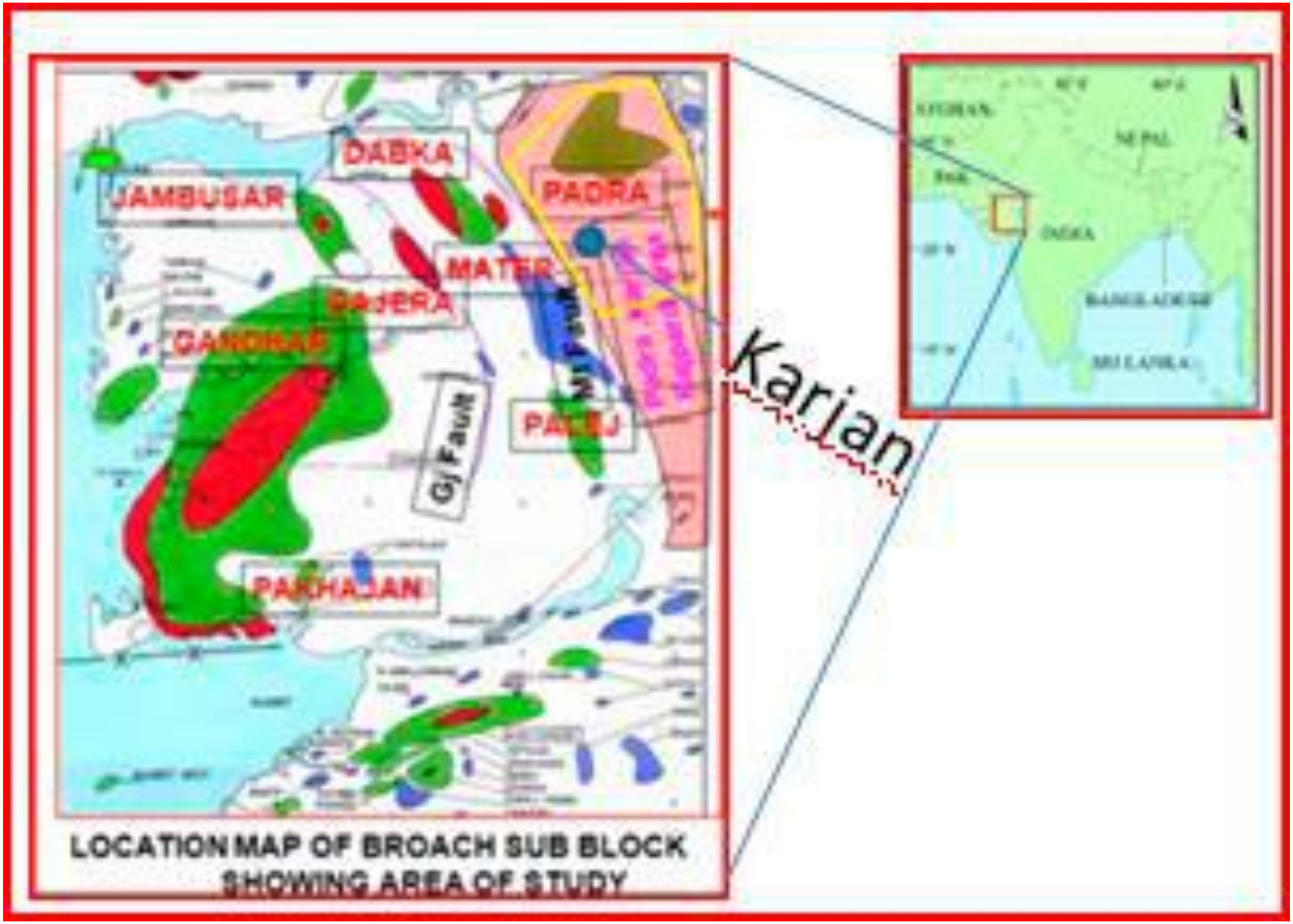

Figure 1. Location map showing area of study.

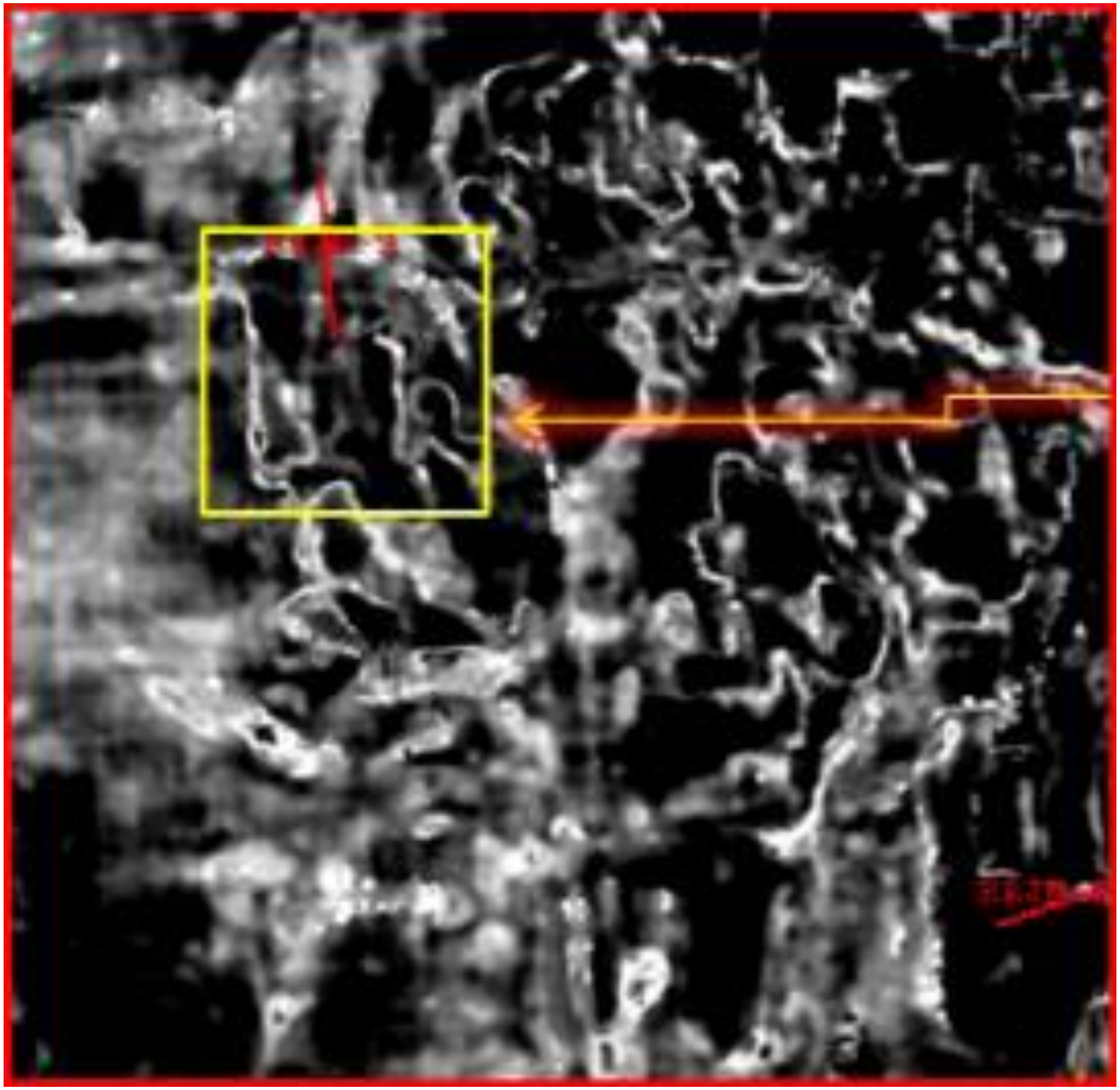

Figure 2. Seismic attribute indicating presence of possible extensional fracture in Karjan Prospect. Area in bounded by yellow square is taken up for Fracture modeling.

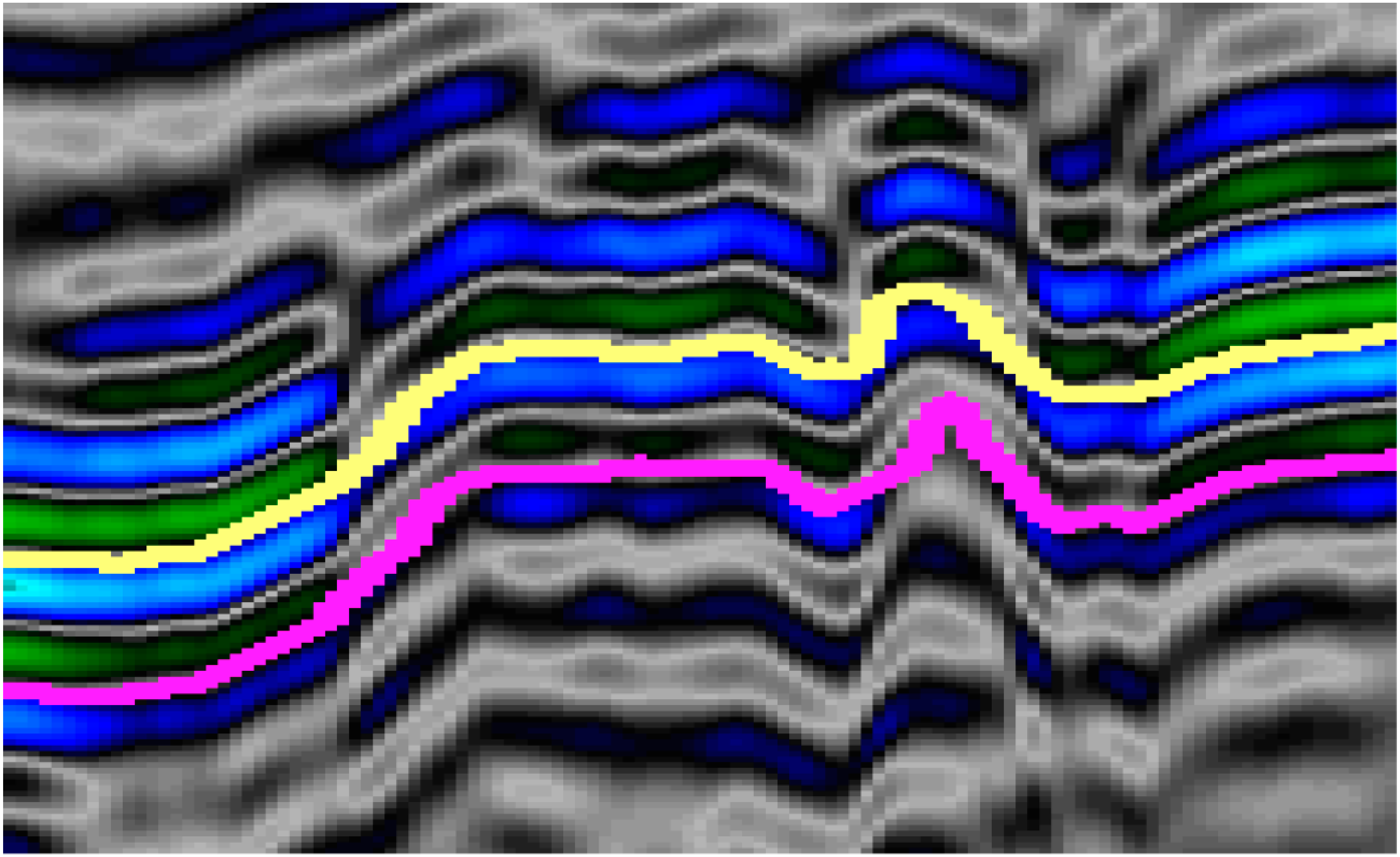

Figure 3. Showing the seismic reflection near the trap top. Yellow is mapped as top of trap surface and event below (pink colour) mapped as sub-layer base.

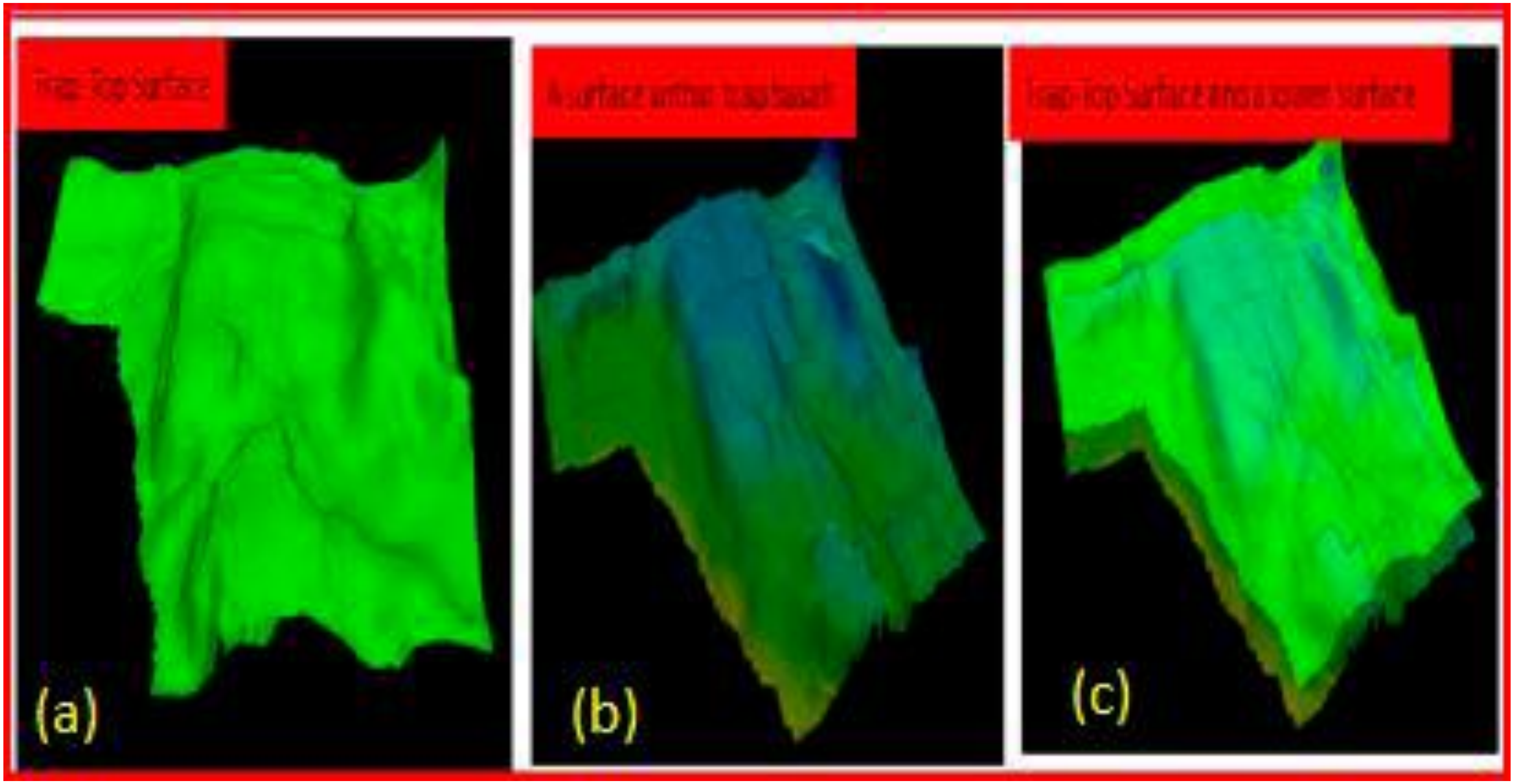

Figure 4. Input for creation of Geo-cellular volume: (a) Top of trap surface; (b) surface of sub-layer base; and (c) bounding surface of 3D volume taken for creation of Geo-volume.

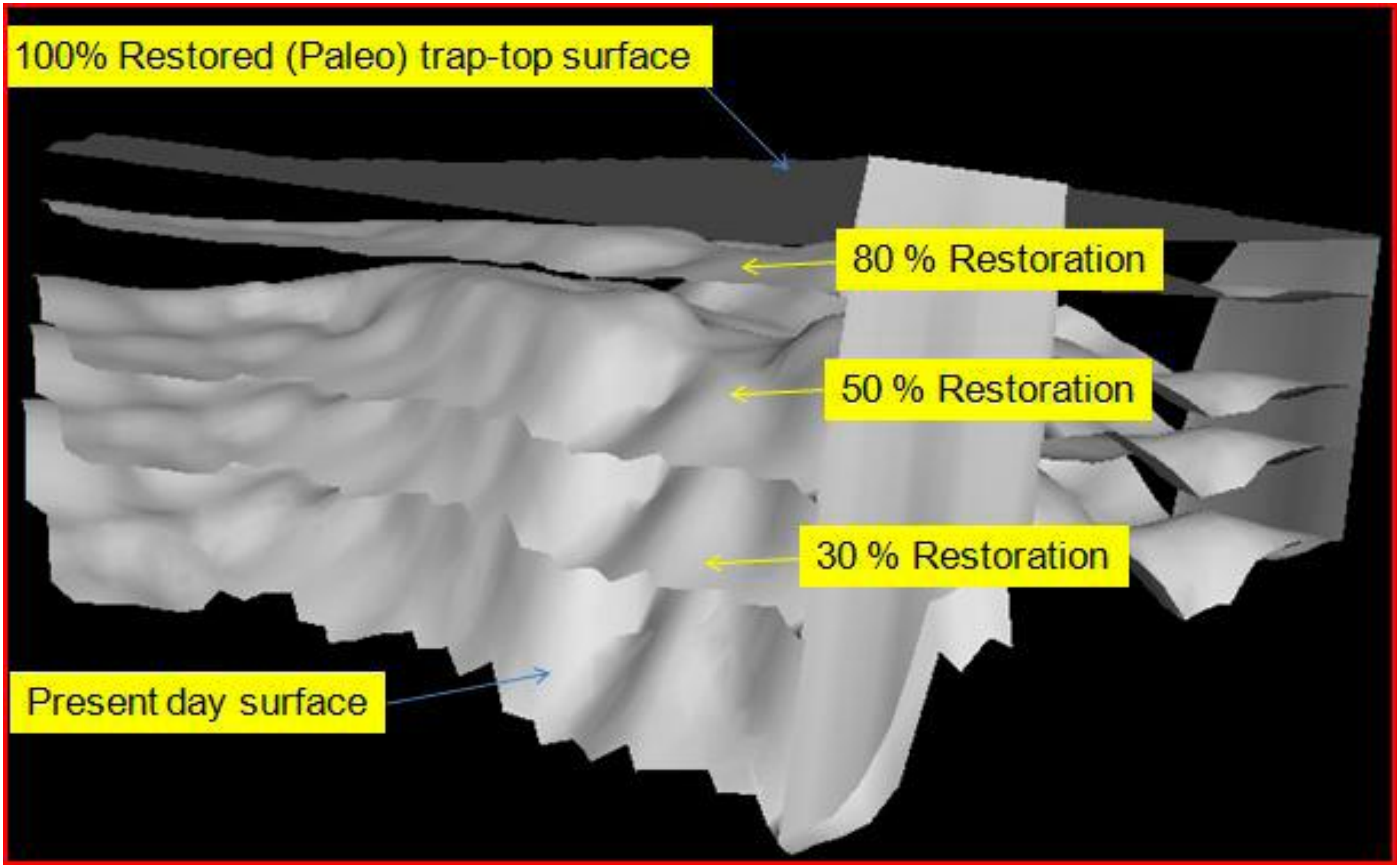

Figure 5. Shows the reverse restoration of present day surface to the initial state of surface. 100% restoration has flattened the surface (assumed as initial surface).

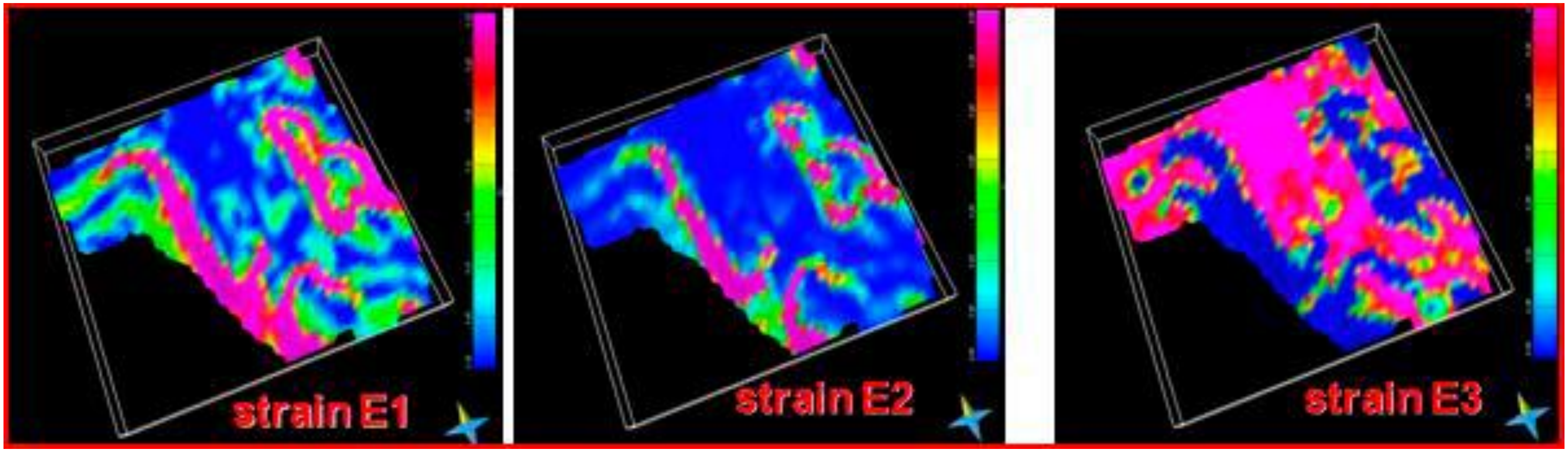

Figure 6. Strain distribution pattern, pink colour representing high strain value, pink.

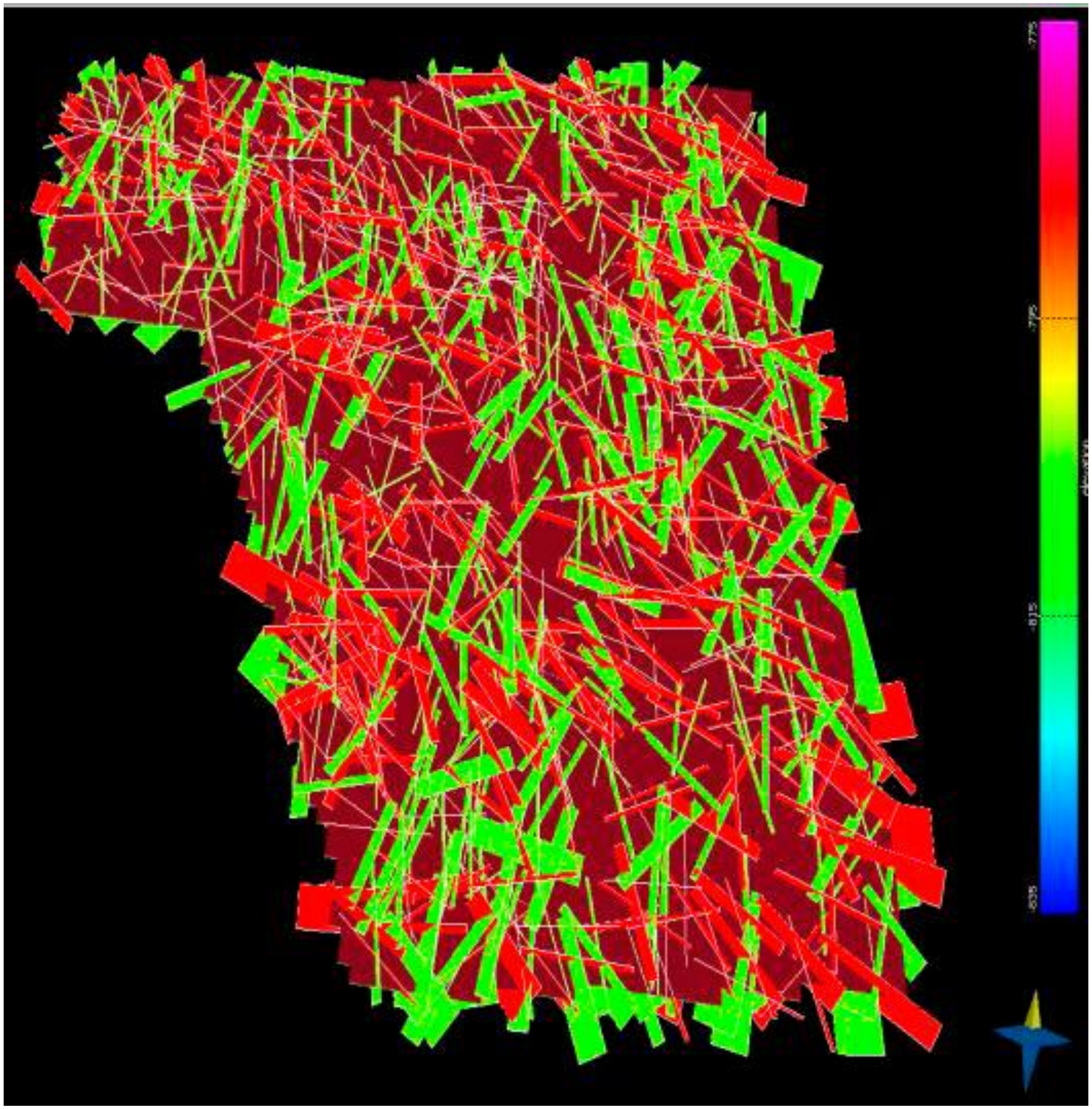

Figure 7. Two set of 3D DFN generated is shown in green and red color as probable fracture networks plane.

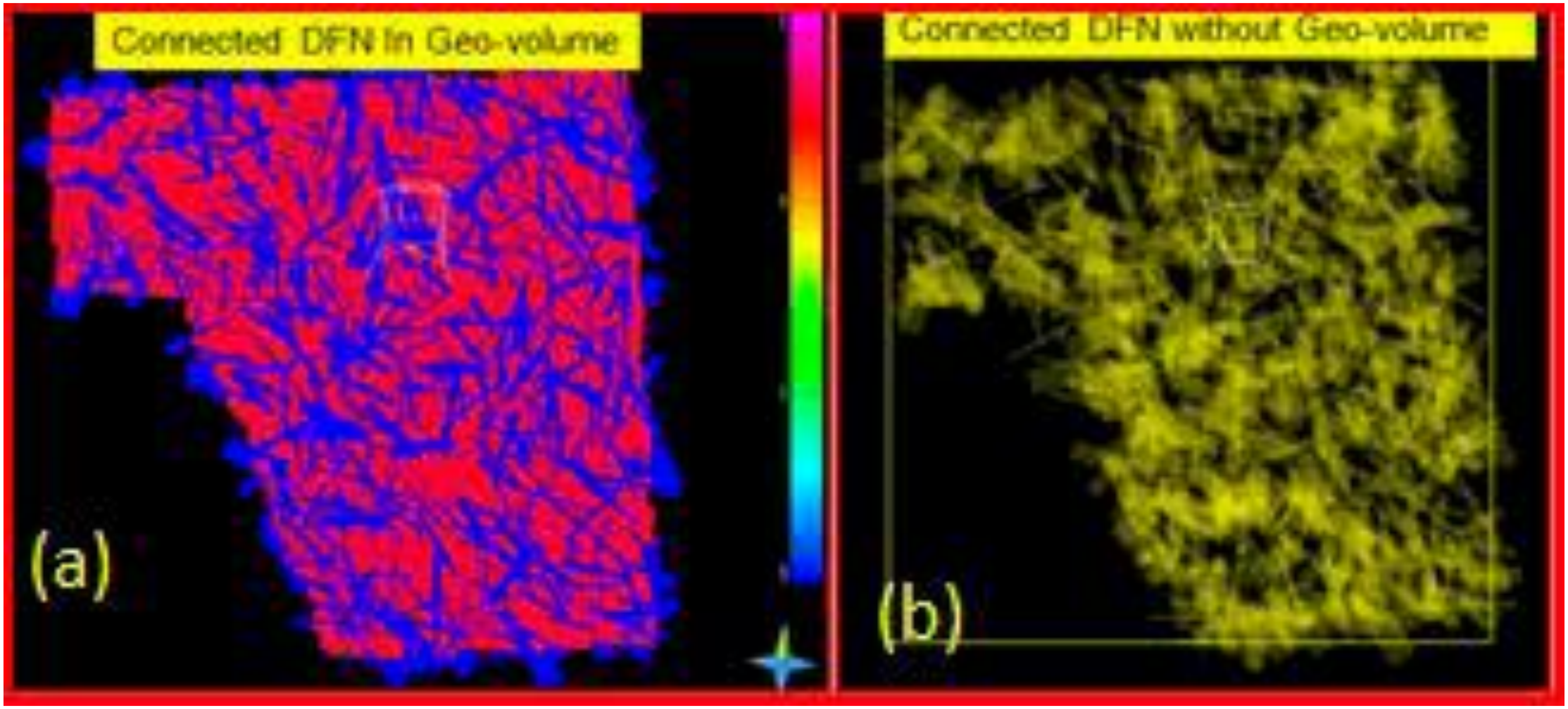

Figure 8. Connected DFN is shown with and without Geo-volume. The intensity, orientation and spacing distribution can be seen. Connectivity analysis of DFN with geo-volume (a) and without Geo-volume.

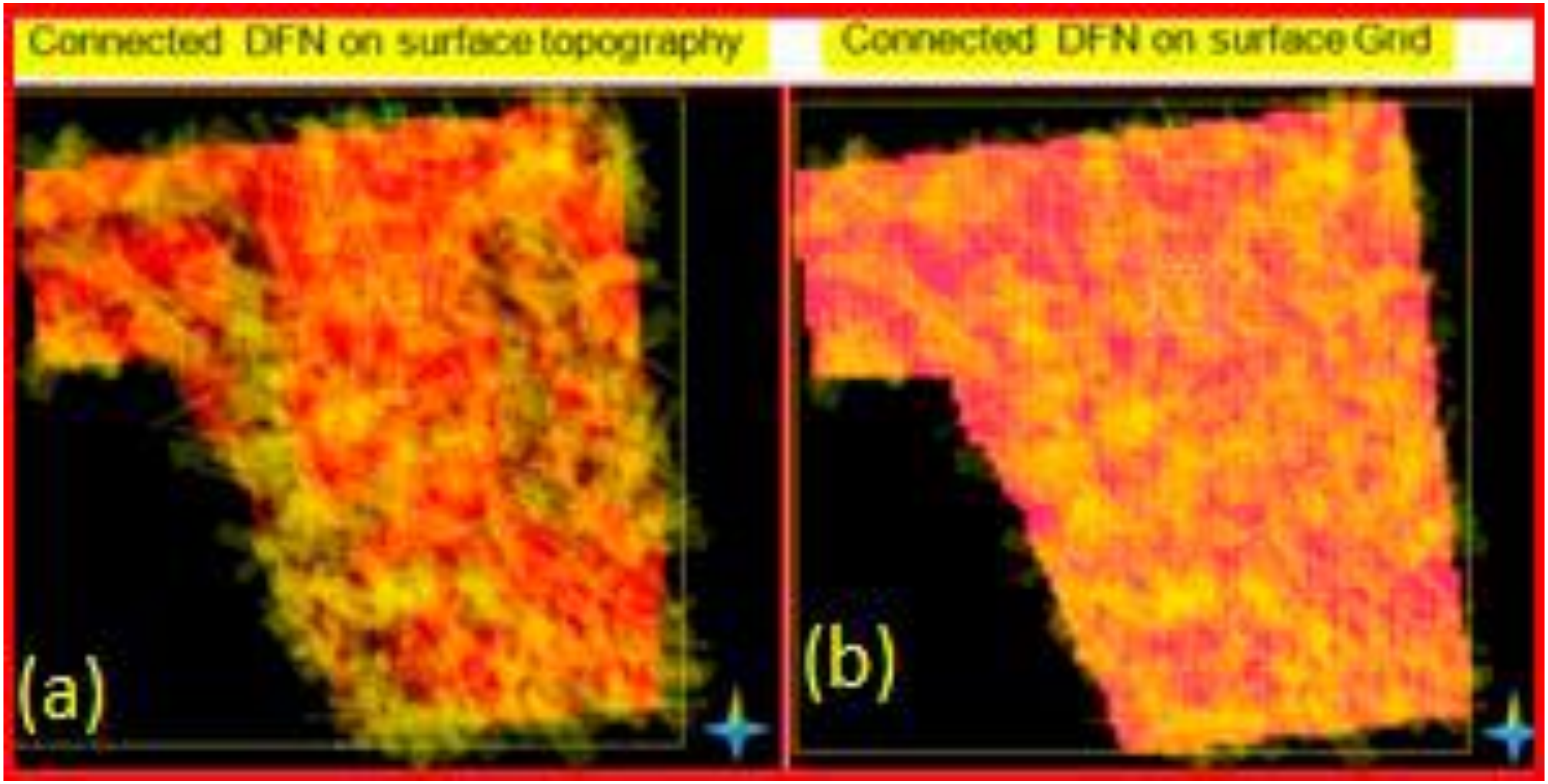

Figure 9. Connected DFN is shown on surface topography (a) and grid (b). The intensity of DFN's along faults can be seen clearly.

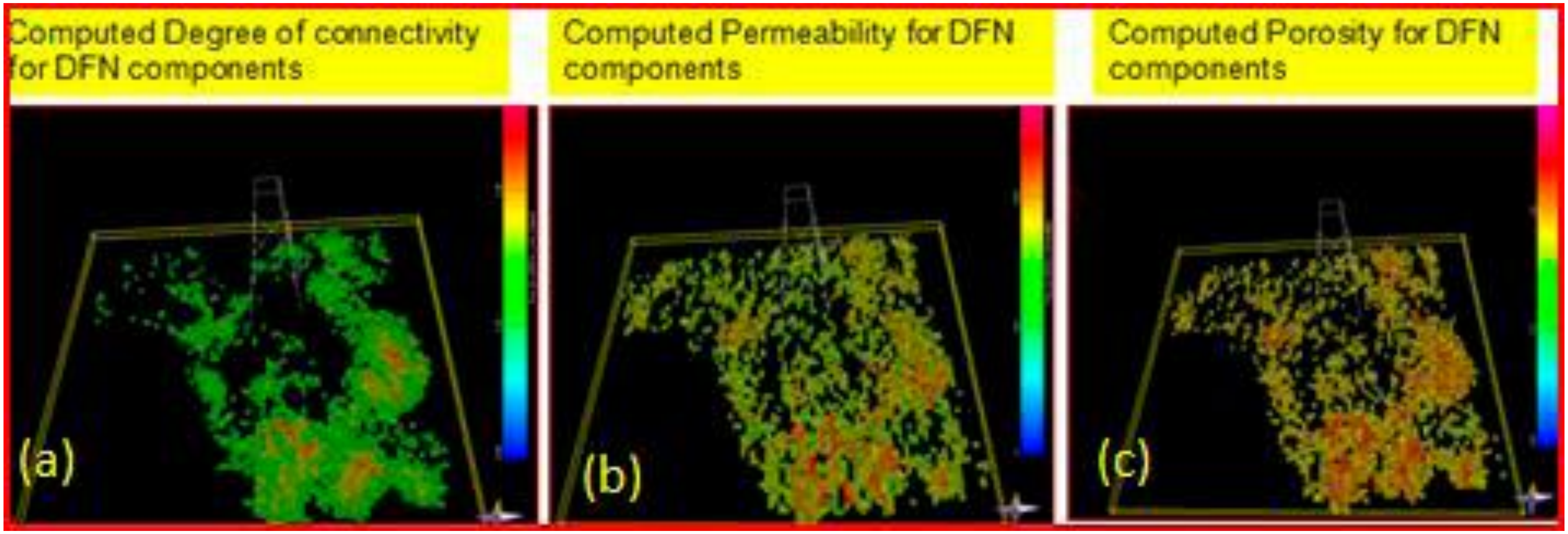

Figure 10. Parameters computed for connected DFN's. Parameters are showing the spatial variability of reservoir parameters.

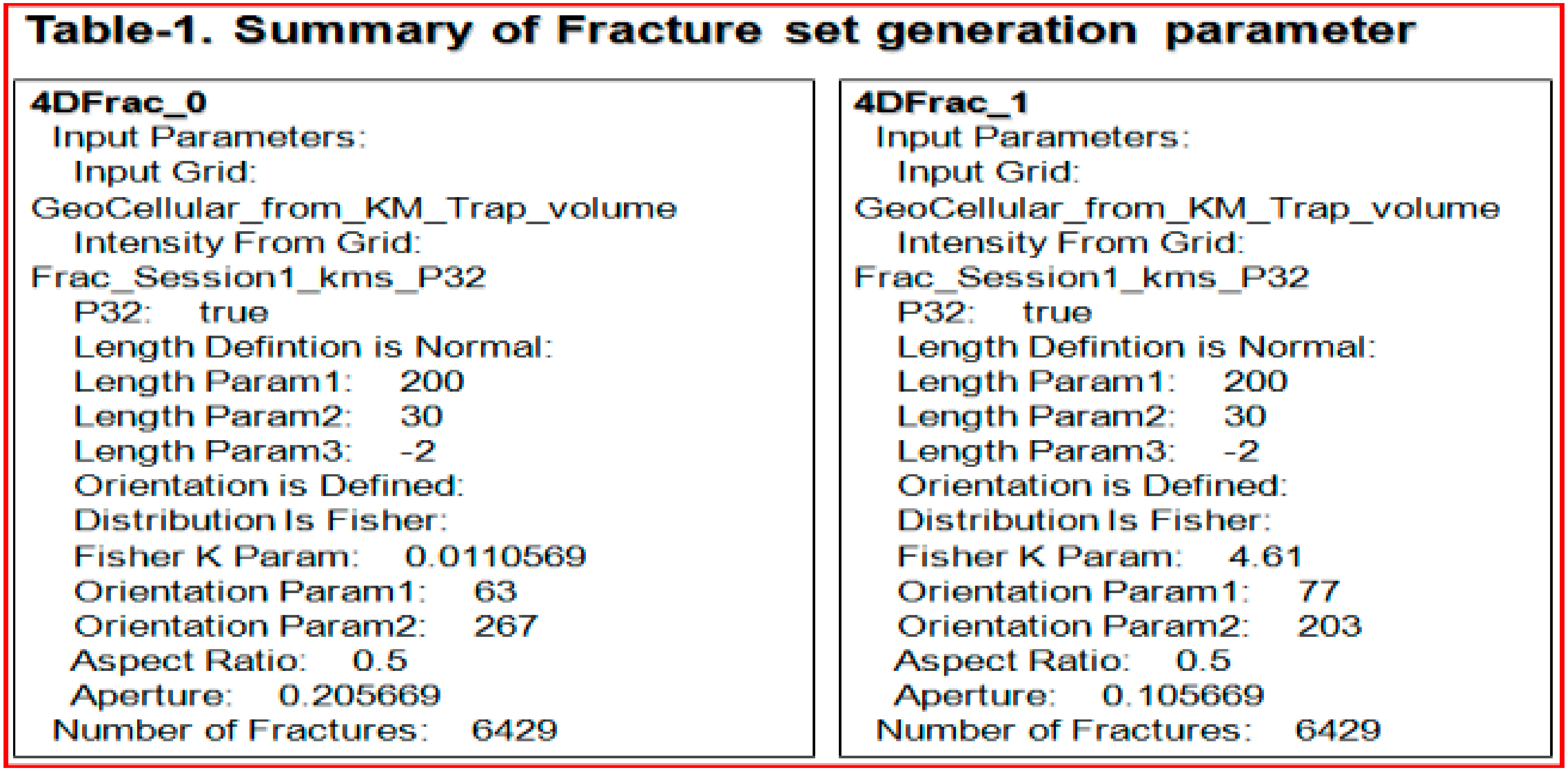

Table-1. Summary of Fracture set generation parameter

```
4DFrac_0
 Input Parameters:
   Input Grid:
GeoCellular_from_KM_Trap_volume
   Intensity From Grid:
Frac_Session1_kms_P32
   P32:    true
   Length Defintion is Normal:
   Length Param1:    200
   Length Param2:    30
   Length Param3:    -2
   Orientation is Defined:
   Distribution Is Fisher:
   Fisher K Param:    0.0110569
   Orientation Param1:    63
   Orientation Param2:    267
   Aspect Ratio:    0.5
   Aperture:    0.205669
 Number of Fractures:    6429
```

```
4DFrac_1
 Input Parameters:
   Input Grid:
GeoCellular_from_KM_Trap_volume
   Intensity From Grid:
Frac_Session1_kms_P32
   P32:    true
   Length Defintion is Normal:
   Length Param1:    200
   Length Param2:    30
   Length Param3:    -2
   Orientation is Defined:
   Distribution Is Fisher:
   Fisher K Param:    4.61
   Orientation Param1:    77
   Orientation Param2:    203
   Aspect Ratio:    0.5
   Aperture:    0.105669
 Number of Fractures:    6429
```

Table 1. Summary of fracture set generation parameters.

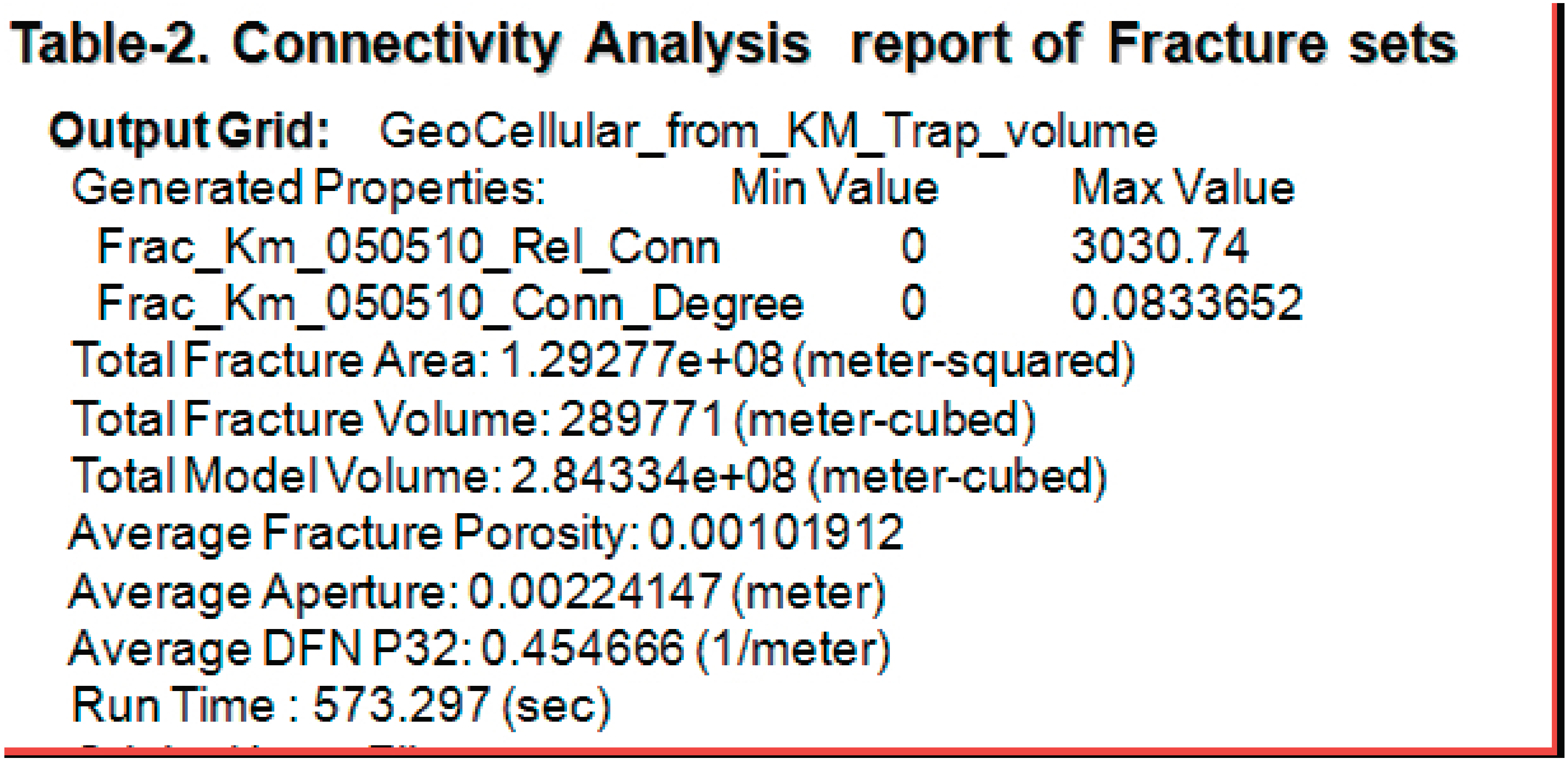

Table-2. Connectivity Analysis report of Fracture sets

```
Output Grid:   GeoCellular_from_KM_Trap_volume
 Generated Properties:           Min Value        Max Value
  Frac_Km_050510_Rel_Conn             0           3030.74
  Frac_Km_050510_Conn_Degree          0           0.0833652
 Total Fracture Area: 1.29277e+08 (meter-squared)
 Total Fracture Volume: 289771 (meter-cubed)
 Total Model Volume: 2.84334e+08 (meter-cubed)
 Average Fracture Porosity: 0.00101912
 Average Aperture: 0.00224147 (meter)
 Average DFN P32: 0.454666 (1/meter)
 Run Time : 573.297 (sec)
```

Table 2. Connectivity analysis report of fracture sets.