PS Fracture and Deformation Band Visualization Using Full-Resolution 3D Ground Penetrating Radar (GPR) in Cretaceous Carbonates*

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Abstract

Fractures are important conduits in many reservoirs. Yet, assessing fracture patterns is not an easy task as most fracture analyses rely on cores/bore walls or two-dimensional outcrop analogs. A newly developed acquisition system of full-resolution 3D Ground Penetrating Radar (GPR) and subsequent migration of the data allow, for the first time, to image fracture and deformation band networks in three dimensions.

Some of the crucial elements of the full-resolution 3D GPR acquisition are:

- a rotary laser positioning system for centimeter precise positioning of the antenna
- the simultaneous acquisition of 100 and 200 MHz antenna
- a regular and dense grid acquisition (5 and 20 cm) of GPR profiles for the high resolution characterization of fractured carbonates

The datasets are processed using the following flow: dewow, time zero correction, gain application, background removal and 3D migration. Faults and fractures are visible on GPR data as zones of higher amplitude due to the generation of diffractions along the fractures.

Several 3D cubes were acquired at two sites. In Cassis (SE France), a karst-enhanced fracture system in Barremian rudist-bearing strata is imaged with great clarity to a depth of 25 m. A simultaneously performed outcrop-based fracture analysis recognizes fractures of all sizes but the 3D GPR data adds important information in regards to the vertical fault terminations and fault systems that are parallel to the outcrop. Furthermore, solution-enhanced faults and randomly distributed karst caves are visible on 3D data.

Similarly, in the Madonna della Mazza quarry, Maiella Mountains Italy, near- vertical deformation bands and the cross-cutting relationships are clearly visible in the GPR data to a depth of 13 m in Maastrichtian rudist grainstones. The 3D GPR data reveal bedding and even sedimentary structures that are not visible on the quarry wall. Likewise, the six sets of deformation bands observed in the quarry are imaged by the 3D GPR with great clarity. In particular, the near surface time slices display a very similar pattern as described by Tondi et al., (2006) on the quarry floor. In addition, when the semblance algorithm attribute is applied these deformation bands can be followed for more than 10 meters depth and allow the determination of crosscutting relationships with other fractures and dipping layers in order to realize kinematic studies and more precise flow modeling.

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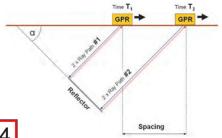
FULL-RESOLUTION 3D GPR

A newly developed acquisition system of full-resolution 3D Ground Penetrating Radar (GPR) and subsequent migration of the data allow, for the first time, to image fracture and deformation band networks in three dimensions. So-called 3D GPR data-sets are often spatially aliased, so that a high degree of interpolation is necessary to reconstruct geometries between parallel profiles. Minimum requirement to acquire unaliased true 3D GPR is quarter-wavelength as spatial sampling.

Nyquist criterion for spatial sampling:

to properly image the reflector, the difference between the two Ray Paths has to be less than wavelength/2



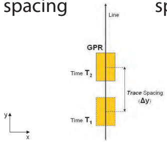
Therefore, for angles of 60 degrees or larger: Spacing < wavelength / 4

Quarter-wavelength requirement is needed in both In-Line and Cross-Line directions

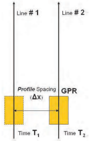
In-Line spacing = ***Trace*** spacing --> distance between two subsequent radar traces

Cross-Line spacing = ***Profile*** spacing --> distance between two subsequent profiles

Trace spacing



Profile spacing



Survey Design:

100 MHz antenna, Trace spacing = ***5 cm***
Profile spacing = ***20 cm***

200 MHz antenna, Trace spacing = ***5 cm***
Profile spacing = ***10 cm***

12 3D GPR surveys in ***11 days***, ***11000 sqm*** acquired!

Quarter of wavelength limits:

frequency = 100 MHz --> ***25 cm***

frequency = 200 MHz --> ***12.5 cm***

Essential survey approach:

A) ***High precision GPR Positioning***

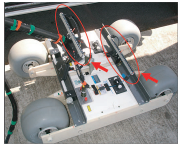
B) ***Dense and regular survey grid***

EQUIPMENT AND ACQUISITION METHOD

1 ***Single Channel 100 MHz GPR Antenna***

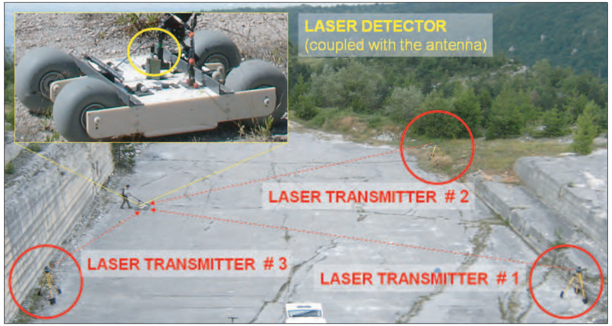
2 ***Dual Channel 200 MHz GPR Antenna***

3 ***Rotary Laser Positioning System***



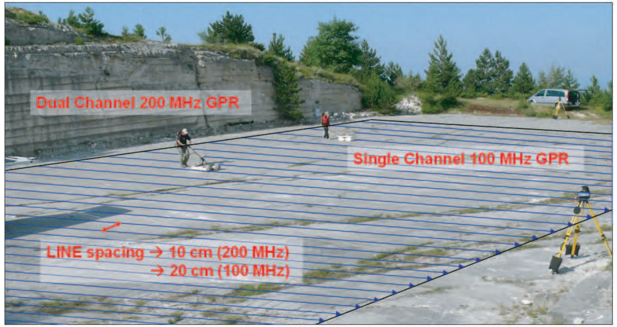
4 ***LED-based Guidance System***

A) *Centimeter Positioning* of the antenna



Three Transimitter Units record coordinates of GPR antenna

B) *Regular* and *Dense* grid in acquisition



LED guidance tool shows how to follow the survey tracks

PROCESSING FLOW

Fusing: GPR and laser data are fused together (x, y, z coordinates are assigned to each radar trace)

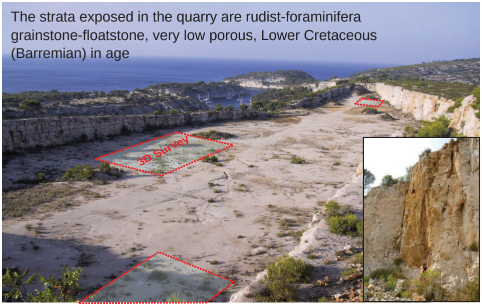
Dewow & Gain: Low frequency components are removed and a gain curve is applied to preserve amplitudes within each datasets

Time Zero Correction: Each trace is adjusted to a common zero value

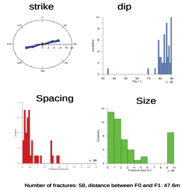
Background Removal: The reflection from air/ground interface is removed

Migration: A 3D migration algorithm is applied to collapse hyperbolas into their apex and reconstruct subsurface target geometries

SOLVAY QUARRY, CASSIS (France)

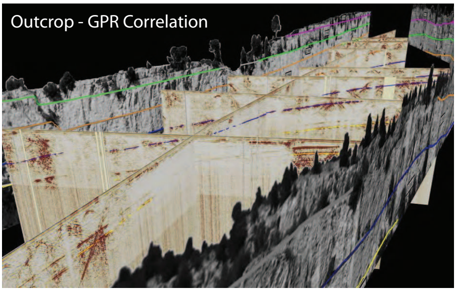


The strata exposed in the quarry are rudist-foraminifera grainstone-floatstone, very low porous, Lower Cretaceous (Barremian) in age

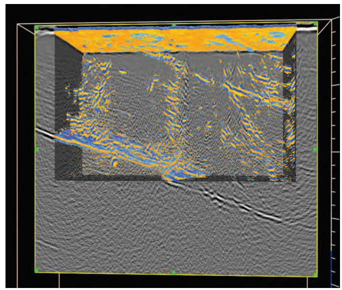


Key Findings:

1. Most fractures are tension-gashes (aperture 1-5 mm)
2. Two fracture populations:
   - Large fractures corrridors (>10 m)
   - Small fractures in en echelon arrays
3. Spacing 0-1 m and few of them are 2 - 2.5 m
4. Fractures strike N080 and dip 80° to 90°
5. Many fractures are solution enhanced

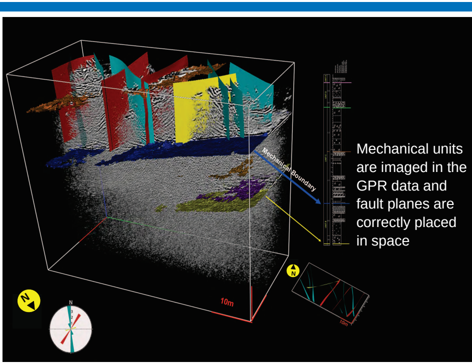


The 2D GPR lines are placed correctly in spaced and correlated to the outcrop in the quarry wall

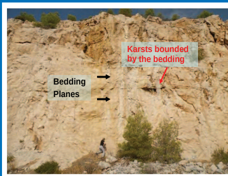


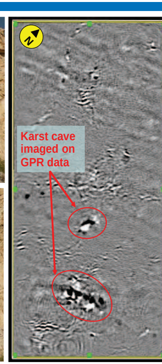
Volume amplitude rendering of GPR volume to show the fracture trajectories

The fractures are shown by the strong-amplitudes reflection pattern

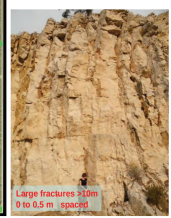


Mechanical units are imaged in the GPR data and fault planes are correctly placed in space





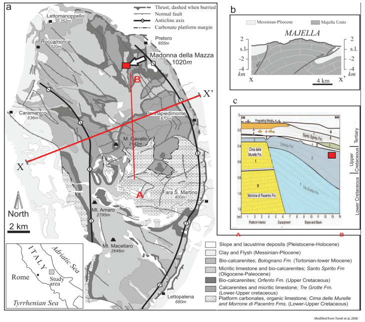
The solution enhanced-fractures and randomly distributed karst caves are visible on the GPR data



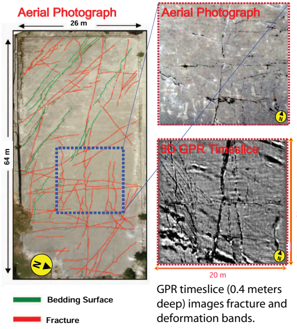
MADONNA DELLA MAZZA QUARRY, MAIELLA (Italy)

The Maiella anticline is a thrust-related, asymmetric anticline composed of carbonates of **Lower Cretaceous** to **Miocene** in age.

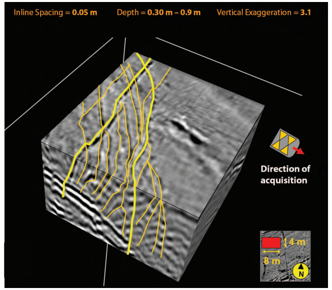
The **anticline** is oriented along an axis curving from NW in the northern part and to NE in the southern part. The **quarry** is located on the northeastern limb of the Maiella anticline.



FULL-RESOLUTION 3D GPR IMAGING



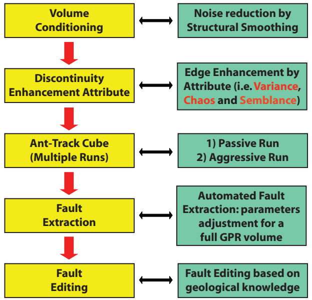
GPR timeslice (0.4 meters deep) images fracture and deformation bands.

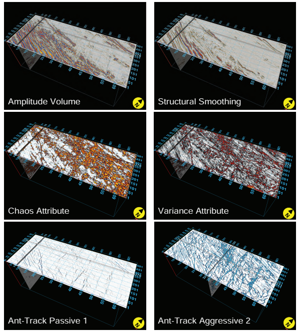


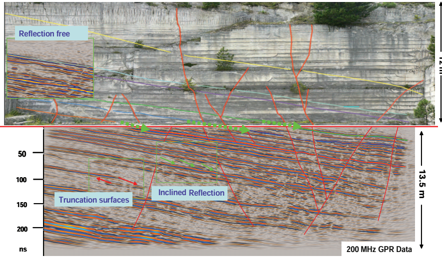
Full-resolution 3D GPR: 250 MHz data imaging a swarm of deformation bands and their crosscutting relationships

ANT-TRACK FRACTURE INTERPRETATION

Ant-Track Workflow in Petrel







GPR ***Facies*** and Outcrop ***Correlation***

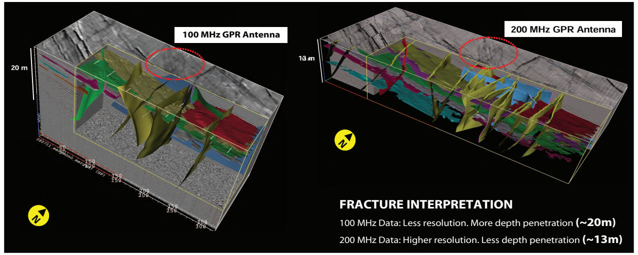
Bedding surfaces are better visible in the GPR data than in the outcrop.

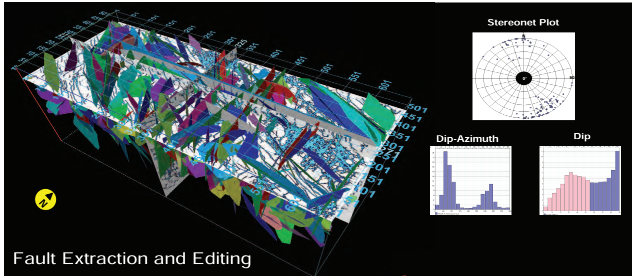
Three ***GPR facies***:

1) **Reflection free** (correlated to the massive carbonate lithology)

2) **Truncation surfaces** (indicate the discontinuity of strata)

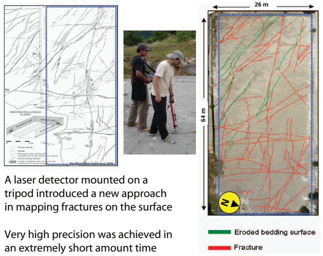
3) **Inclined reflection** (correlated to the fore-set bedding)





The **Ant-Track** workflow has been applied **for the first time to 3D GPR** data. A specific workflow is required for such a complex 3D volume. The geological knowledge is needed during fault extraction and editing.

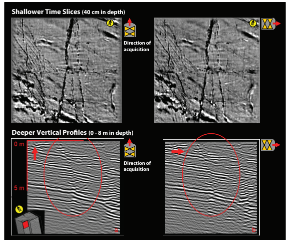
Mapping with Laser Positioning System



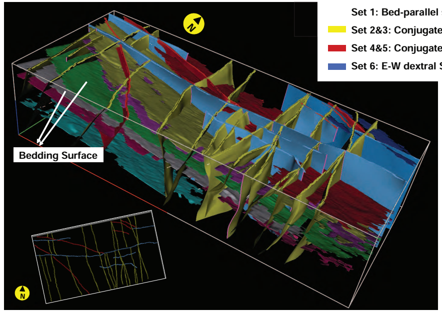
A laser detector mounted on a tripod introduced a new approach in mapping fractures on the surface

Very high precision was achieved in an extremely short amount time

Dual-Polarization Experiment



Both in shallow and deep portions **NO difference** in image quality!

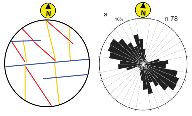


Set 1: Bed-parallel stylolites

Set 2&3: Conjugate sets NNW orientation normal dip-slip

Set 4&5: Conjugate sets WNW orientation normal dip-slip

Set 6: E-W dextral Strike-slip



Simplified cross-cutting relationship

The **oldest** set of the fractures is the Bed-parallel stylolites, the NNW and WNW conjugate sets **contemporaneously developed** and the EW dextral strike slips are the **youngest** set of fractures.

CONCLUSIONS

1) Three-dimensional Ground Penetrating Radar (GPR) surveys **accurately image fractures** and deformation bands in the subsurface

2) A **regular and dense acquisition grid** of GPR profiles is the prime requirement for the high resolution characterization of fractured carbonates

3) Characterization of fractures in terms of orientation, development in the subsurface and interconnectivity can now be **linked with outcrop derived stratigraphic and tectonic information**: this allows to determine crosscutting relationships with other fractures and dipping layers in order to realize kinematic studies and **more precise flow modeling**