CORE STRUCTURAL ANALYSIS
& FRACTURE GONIOMETRY

TECHNICAL NOTES

PREPARED BY,

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Contents

1. INTRODUCTION

CORIAS brings vast experience in high precision core reorientation, fracture description and structural analysis along with invaluable worldwide record.

We have managed several worldwide projects including both offshore and onshore onsite core fracture description & structural analysis as well as studies performed on both recent and old cores at core store/laboratory environment.

Our structural geology team provides ***invaluable solutions in 3D reservoir characterization***.

Among the main deliverables is the prediction of the optimal drilling direction from oriented core studies thus intercepting the fracture network in order to maximize reservoir performance, whether enhancing production or for more effective stimulation.

The ***CORIAS*** high precision ***AS3D*** computerized goniometric system is a portable structural analysis tool that allows fracture description & structural analysis to be performed directly on the rig site, maintaining integrity of core samples before cutting and transporting.

This proven approach ensures reliable and highly accurate results providing ***real time structural analysis*** and significant rig-time savings. Alternatively, the *AS3D* computerized goniometer can be used for the same purpose in any core store/laboratory environment.

2. CAPABILITIES AND CASE HISTORIES

Please refer to the experience history reference list on our website (www.corias.com) , which reflects the vast experience that we gained in many projects all over the world, offering complete solutions in high precision core reorientation, fracture description and structural analysis.

These case histories included comprehensive integration of the directly acquired core data and fracture description analysis with image logs to assist and calibrate the logs for proper future interpretation.

We have studied over 100,000 ft of core all over the world in many countries.

2.1 EXPERIENCE HISTORY – SUMMARY

This work included great many comprehensive fracture description and structural analysis studies, and advanced projects, globally, and through various reservoir zones in the Middle East area and around the world , including:

- ***UAE: Many projects for ADNOC, ADMA, ZADCO, ADCO, Bunduq, Total ABK; Qatar: QP, Dolphin; Yemen: Total Yemen; Oman: PDO; Kuwait: KOC, Joint Operations; Iran: Elf Petroleum Iran, Total, Edison; Saudi: Aramco, Luksar, KJO; Kurdistan: Heritage, Crescent, MOL, Hunt, Genel, Oryx;***
- ***Europe: Total, BP Norway, Norsk Hydro, Lundin, Exxon Mobil, Wintershall, Neptune Energy,***
- ***Other areas:Cabot oil, Rosetta, Gazprom, Shell, PDVSA, TPAO, JASLO,***

These case histories included comprehensive integration of image logs and directly acquired core fracture description analysis to calibrate the logs and assist in proper future interpretation.

2.2 PUBLISHED PAPERS

Upon request, we will be happy to present any of the following papers and elaborate on the core/image logs integrated studies.

GEO 2002

Paper Title: 'Balal Field, Upper Arab Reservoir: Core Based Micro-Structural Model and Impact on Permeability Field Definition'

We have presented this paper in the 'Geo 2002' conference in Bahrain (copy is available on request), a core based micro-structural study case history from the ***Arab** formation in the Iranian field Balal*.

SCA 2004

Paper Title: 'Integrating Core Data and Image Logs: The Critical Steps in Modelling a Fractured Carbonate Reservoir'.

We have presented this paper in the 'SCA 2004' conference that was held in Abu-Dhabi. This paper presents five case histories that describe the mapping of the fracture network using both core and borehole image data. The paper shows how the data from the two methods can differ and how reconciliation can lead to a better understanding of the formation being studied.

IPTC 16661 MS- 2013

Paper Title: 'Reliable Fracture Characterisation n Value Addition Through Special Core Reorientation'

We have presented this paper in the 'IPTC International Petroleum Technology' conference in Beijing (copy is available upon request), a comprehensive campaign of core based fracture analysis that was carried out on more than 7,000ft of deep tight carbonate (over 14500ft TVD and 3pu avg. porosity and 0.1 mD avg. perm) cores in Kuwait, spread over a number of wells covering a large area of over 1000sq km.

Paper Title: 'Field Development and Well planning in Tight Carbonate Reservoir using Fracture Characterization and in-situ Stress mapping from core reorientation studies: Kuwait Case Study'

3. AIM OF THE STUDY - FRACTURE LOGGING & DESCRIPTION

The study will be focused in:

- Acquiring all the necessary detailed data, such as structures distribution, porosity, fillings, directional parameters, etc.
- Evaluating the implication of fracture systems distribution in the reservoir behavior.

3.1 STUDY OF TECTONIC & SEDIMENTARY FEATURES

The structural analysis consists in a detailed acquisition, description and interpretation of all planar and linear structures, including:

- **Tectonic Features:** Natural Fractures (Partially Open Fractures, Open Fractures, Cemented Fractures, Faults, etc.), Tectonic Stylolites;
- **Stress-Related Features:** Induced fractures;
- **Sedimentary Features:** Dissolution seams, Sedimentary Stylolites, Joints, Bedding, Unconformities, etc.

Figure 1 - Examples of features: A - Sedimentary Stylolites; B – En-echelon partially open fractures with calcite filling; C – Surface of a Stratification Gliding Plane with respective striation; D – Fault.

This will allow a comprehensive micro-tectonic (core scale) study based on an inventory of main structural events affecting the cored section.

This study consists on a systematic measurement and consequent characterization of planar and linear structures relevant to the reservoir behavior, which includes:

- Characterization of type of discontinuities;
- Location of structures and their distribution, density, spacing, true frequency, etc.;
- Length of the features as well as their aperture, continuity, abutting, etc.;
- Initial relative orientation considering the dip vs. core axis (on both deviated and vertical wells) and later re-orientation based on calibration with information from oriented core, borehole images, seismic maps, etc.;

- Description of the mineralization and/or fillings;
- Detailed characterization of stylolites and their contribution to reservoir anisotropy;
- Study of induced fractures and characterization of the in-situ horizontal actual stress.

4. CORE STRUCTURAL ANALYSIS

The work typically includes the following three steps:

1) **Acquisition** of geological features;
2) **Processing** of the acquired data*;*
3) **Restitution** of the processed data into workable and manageable data.

The process is done directly on core and consists of an exhaustive collection of tectonic and sedimentary structures in order to obtain a dip-meter log and transferable database with the information regarding the orientation (dip and strike) and position (depth) of all the acquired features.

4.1 DATA ACQUISITION

4.1.1 Reconstruction of the Core into Continuous Intervals

The acquisition of all geological data is done with an outstanding accuracy and expertise, always following a strict conduct of "check and double-check".

It is critical to complete this important work, which consisted of the reconstitution of the cores, from fragments to obtain a maximum connected length. A reference line is drawn on each connected length of core. The ready access to the entire cored interval is very important. Using pre-split inner tubes (half moon, lasercut) made it easier to access the full length of the cores, and to draw reference lines to align non-connected core fragments that are separated by breaks and fractured zones.

By lifting the top half-shell of these inner tubes off the core, alignment of the core pieces and proper marking of the Master Orientation Line (MOL) can be made directly on the full length of the core. In these specific applications in the past, using a ***longitudinal saw*** to cut the full length of standard inner tubes into two halves was always associated with mechanical disturbance to the core, with damage along the full length of the core being caused by the cutting blades.

A 'Continuous Interval' is the total length of one or more core pieces that can be unmistakably fitted together.

This task of core reconstitution, from core fragments to the maximum possible connected length of core, is crucial as it will assure the excellence of our study and consequent outcome. After core fitting and confirmation, a reference line is drawn on each connected length of core. The ready access to the entire cored interval is very important, mainly after undergone processing and transport.

The Corias structural analyst is responsible for identifying continuous core intervals which are normally limited by 'spin-offs', rubble zones, missing pieces, breaks due to 'connections while coring' and more. An expert and experienced eye normally is capable of distinguishing "true locks" from non-natural or coring-induced "false fittings".

The pre- split system contributes for continuous intervals to be more confidently identified, eliminating not only the typical problems related to missing "preserved" zones but also random and deliberate saw cuts.

Note: *Saw cuts at the end of each core interval (when cutting steel coupled fiberglass inner tubes) can prevent later reconstruction in the absence of distinguishing marks on the core.*

4.2 THE AS3D SYSTEM

The AS3D (Figure 2) Computer aided by a 3D digitization equipment is considered to be the most efficient and sophisticated geometrical measurement tool (for both linear and planar structures) for study of cores. The AS3D is a fully computerized and direct three-dimensional goniometric digitization system. ***Note:*** *Please see Figure 3for an example of the comprehensive electronic database output.*

Figure 2 – AS3D equipment

The AS3D system is characterized by:

- **Its accuracy to the nearest degree, where the flatness coefficient provides direct information on the quality of the measurements;**
- **Its capacity to determine the structures position (depth) at the nearest millimeter;**
- **Its sophisticated and customizable menu-driven software, which makes the acquisition easier;**
- **The quality of its data and deliverables, including: database, dipmeter logs, stereograms, rosette diagrams, histograms, etc.**

Moreover, the AS3D system ensures that all data acquired is immediately saved in a transferable database and constantly backed up.

4.2.1 DATA RECORDING AND ACQUISITION

The data recording and acquisition is done by the structural analyst with the AS3D computerized tool, allowing the three-dimensional and direct digitization of all relevant planar and linear structures on core.

Note: *The AS3D system is just a supporting tool to the structural analyst for higher accuracy and detailed acquisition and also for time saving. Expertise and experience from our analysts are basic requirements.*

The orientation procedure of structures is variable depending on whether it is oriented core or non-oriented core (and also on whether if it is vertical or deviated well). In general, the acquired features are initially oriented based on the reference scribe line drawn on the core and later they are re-oriented into the real geographic position (*i.e.* all directional properties of the formation, e.g. fracture orientations, sedimentary structures, permeability or any other petrophysical anisotropy, can be referred to the geographic North later).

4.2.2 Core Orientation – Oriented Cores

- The core is oriented using downhole EMS Core Orientation Survey Systems while coring which provides information on the geographic orientation of the core.
- With oriented core, the geographic orientation of the structures is immediately calculated by using the core orientation data.
- Note: In order to directly calculate the geographic orientation of all the acquired features it is mandatory that any used oriented coring method ensures that marks/scratches done on core will be straight along the core.

4.2.3 Core Orientation – None Oriented Cores

- In non-oriented cores, the re-orientation is done by recurring to several methods, including:
- Borehole Image Logs (BHI Logs): statistic investigation and comparison with BHI Logs, e.g. FMI, DSI, FMS, CBIL, BHTV.
- Seismic Structural Dip & Borehole Deviation: If the BHI Logs are not available, other information from several sources (seismic structural dip, borehole deviation, etc.) can be used to determine the real position of the measured structures.
- Note: In case none of the above sources are available there is the possibility of using structural geology maps and stress maps for structural re-orientation.

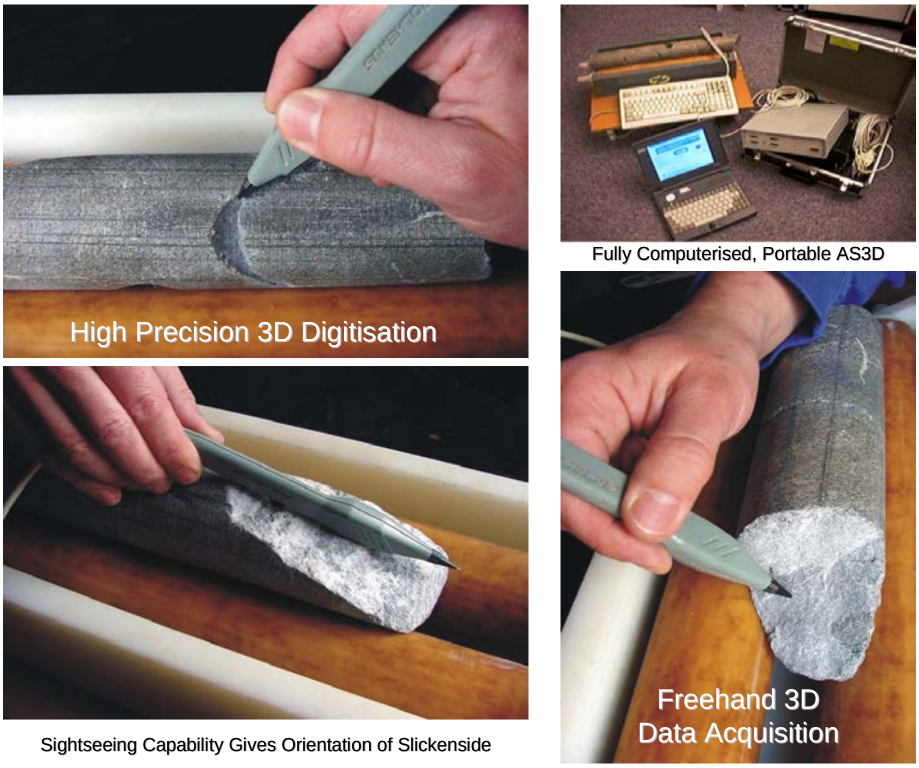

Figure 3 - AS3D: Fully computerised three-dimensional electromagnetic digitization goniometric system

	A	B	C	D	E	F	G	H	I	J
1	**Depth**	**Azimuth**	**Dip**	**Length**	**Depth**	**Nature**	**Thickness**	**Effective**	**Filling 1**	**Percent of**
2	**in feet**				**in meter**			**opening**		**filling 1**
3	9515,866	206	8	9,6	2900,436	Stratification joint	2		A	100
4	9515,981	358	7	9,6	2900,471	Stratification joint	5		A	100
5	9516,470	157	13	9,8	2900,62	Disconformity	0,5		A	100
6	9516,532	111	3	9,5	2900,639	Disconformity	0,5		A	100
7	9517,087	215	19	10	2900,808	Disconformity	0,2		A	100
8	9517,264	126	85	5,1	2900,862	Partially open frac	0,1	0,02	G	100
9	9517,280	102	70	3,8	2900,867	Partially open frac	0,1	0,02	G	100
10	9517,326	125	68	4,1	2900,881	Partially open frac	0,1	0,02	G	100
11	9517,372	86	15	9,8	2900,895	Bedding				
12	9517,392	75	19	10	2900,901	Bedding				
13	9517,448	79	19	10	2900,918	Open Fracture				
14	9518,261	285	75	3,4	2901,166	Partially open frac	0,2		G	100
15	9518,271	109	84	3,8	2901,169	Partially open frac	0,2		G	100
16	9518,274	290	89	3,8	2901,17	Partially open frac	0,2		G	100
17	9518,894	82	17	9,9	2901,359	Bedding				
18	9518,960	94	15	9,8	2901,379	Bedding				
19	9519,150	105	11	9,7	2901,437	Disconformity	1		A	100
20	9519,485	202	2	9,5	2901,539	Stratification joint	0,5		A	100
21	9519,567	227	6	9,6	2901,564	Stratification joint	0,5		A	100
22	9519,573	240	3	9,5	2901,566	Stratification joint	0,5		A	100

Figure 4 - Example of a database with all the acquired features and their respective typology and geometrical characteristics

4.3 DATA PROCESSING

After data acquisition and re-orientation, there is the data processing stage which includes the interpretation and production of all graphical outputs that are then included in the final report.

Highly broken zones are normally impossible to reconstitute and are not included in the survey in order to allow the reliability and quality of the data collected along connected core segments, which is the indispensable data for the re-orientation operation. Although, these zones are included in the study and referred in the processed graphic outputs as remarks.

The most common graphic outputs from data processing are:

- **Dip-meter logs: Dip (Horizontal) vs. Depth (Vertical) charts with all the acquired features plotted and showing their azimuth (Figure 5);**
-
- **Rose Diagram: Showing azimuth or strike distributions of the acquired data (Figure 6);**

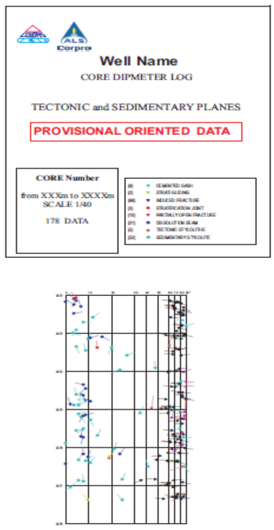

Figure 5 - Example of a dipmeter log.

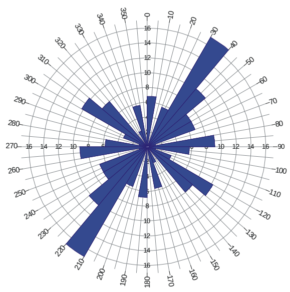

Figure 2 - Example of azimuth rose diagram.

- **Frequency Histograms: Setting out the dip distributions of the acquired data (Figure 7);**

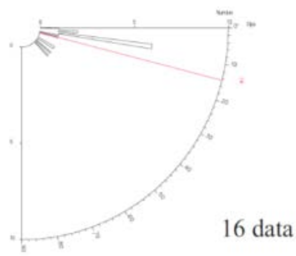

Figure 3 - Examples of frequency histogram.

- **Stereonet Plots: Stereogram plotting all the acquired data and setting out their orientation (dip and strike) (Figure 8);**

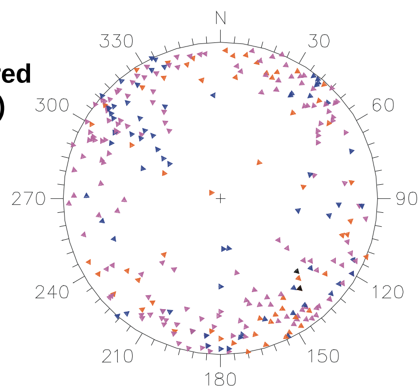

Figure 4 - Example of a stereonet plot.

- **Composite Log: Integration of the dipmeter log or others such as porosity and permeability logs into the main composite log provided by the client (Figure 9).**

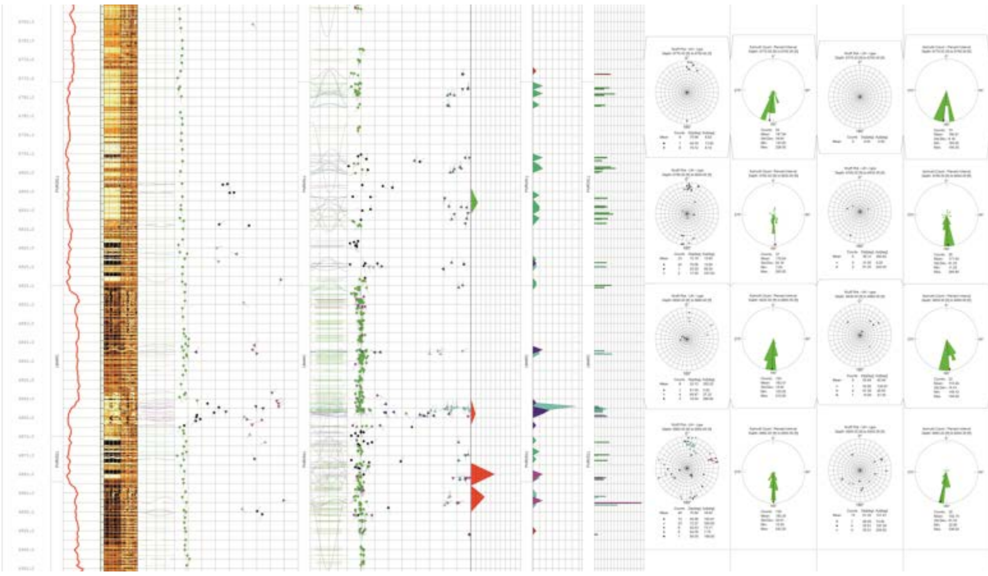

Figure 5 - Example of a composite log with a dipmeter log integrated.

Note: *On both logs and diagrams, a color and shape standard code is used to distinguish sedimentary structures, such as bedding and cross bedding, stratification joints, stylolites, dissolution seams etc., from tectonic structure, such as fractures, gashes, micro-faults or tectonic stylolites.*

According to the client's needs and demand, other graphical/image outputs can be processed and included in the final report. Some examples are shown below in the following sub-chapter.

4.4 Other Graphical Outputs

- <u>**Integration of the structural analysis data from core with the Image log data**</u> (from FMI, DSI, STAR, etc.)

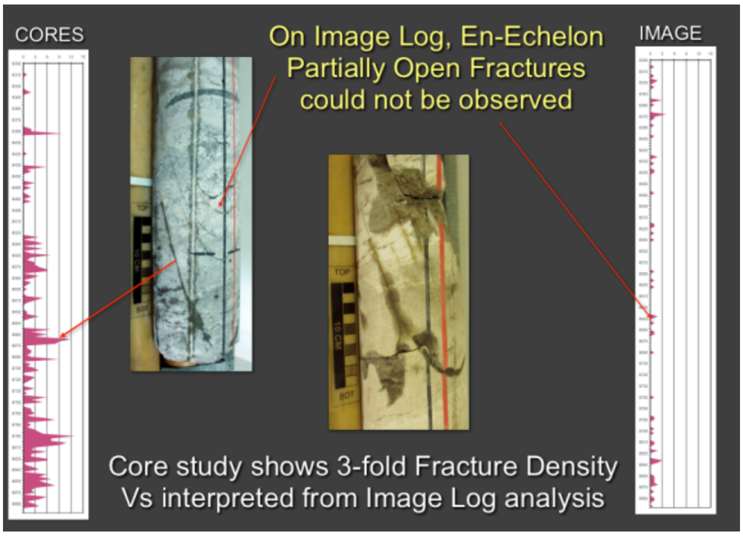

Figure 6 – Data comparison between Core *vs.* Image fractures density logs. This study case show that many 'en-echelon' natural fractures did not appear in the image log, thus leading to an unrepresentative and considerably underestimated fracture density.

- **<u>Structural geology interpretation of core data integrated with image data</u>**, such as schematic structural geology sections (Figure 14), integration of core data within geological maps, study of the main stages of deformation, study of the orientation of the main structural planes (Figure 14), etc.

  Note: *This deliverable requires special conditions, such as extremely good core condition, availability of considerable amount of core and image data from several wells, etc.*

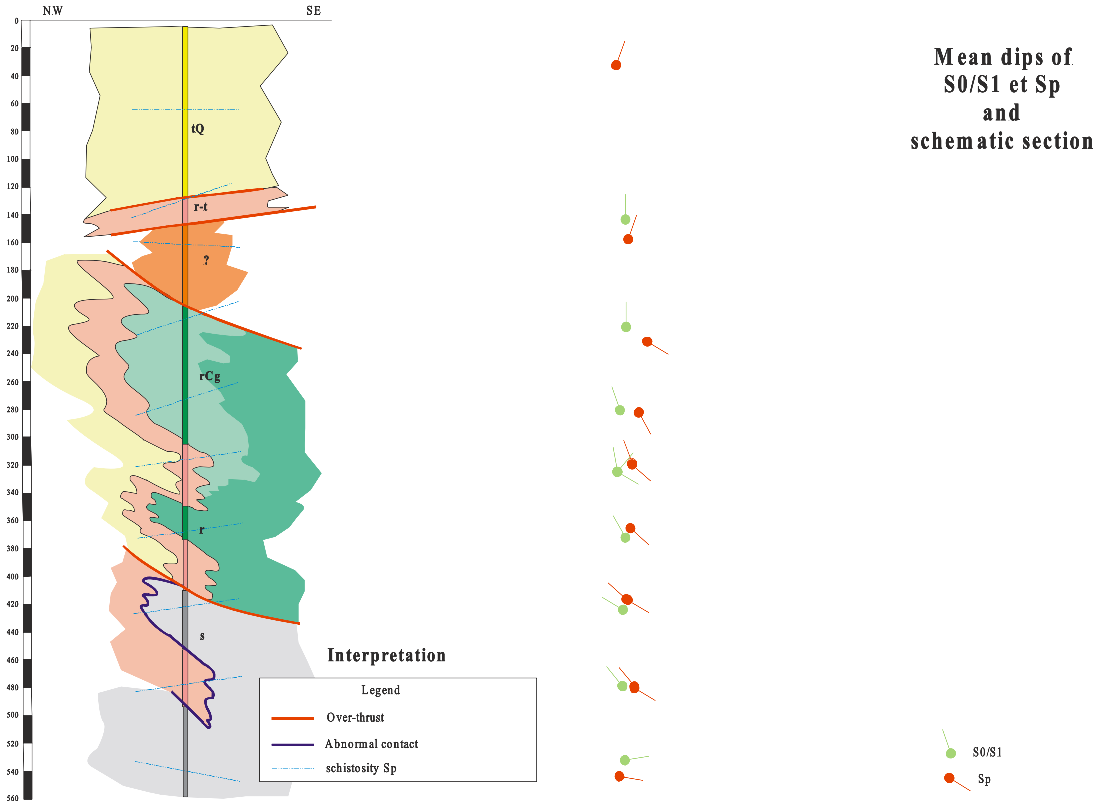

Figure 7 - Example of structural geology schematic section and logs from basement cores with the respective structural planes mean dips information.

- **<u>Statistical analysis of structural core data</u>**, including fracture density per meter (Figure 15), length, opening and thickness of natural fractures (Figure 16) and others.

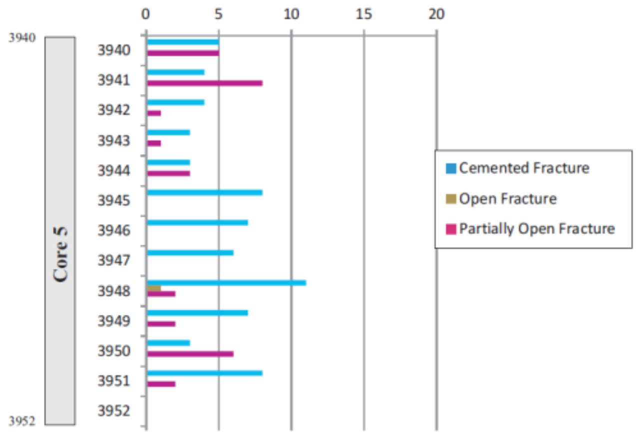

Figure 8 - Example of fracture density per meter log.

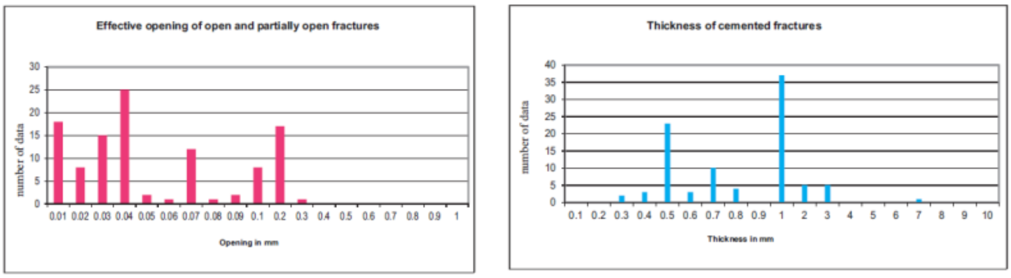

Figure 9 - Example of statistical plots showing opening and thickness of natural fractures.

4.5 Integration Of Core Results And Image Logs

Comprehensive integration of core data and image logs is discussed and can be seen in the attached SCA 2004 paper with participation of our staff: "**<u>Integrating Core Data and Image Logs: The Critical Steps in Modeling a Fractured Carbonate Reservoir</u>**" (Figure 17).

'Integrating Core Data and Image Logs: The Critical Steps in Modelling a Fractured Carbonate Reservoir'

Christian Staffelbach, (Corias), Rob J. Evans and Abdel-Hamid Anis, (Corpro Systems Ltd.)

Abstract

In many of the oil fields in the Middle East the presence of fractures can be the characteristic that defines the flow of fluids within the system. Consequently the identification, description and classification of fractures in such fields are essential to effective formation evaluation and production planning.

This paper will present five case histories that describe the mapping of the fracture network using both core and borehole image data. We show how the data from the two methods can differ and how reconciliation can lead to a better understanding of the formation being studied.

Figure 10 - Abstract of the SCA 2004 paper: "Integrating Core Data and Image Logs: The Critical Steps in Modelling a Fractured Carbonate Reservoir".

5. KEY DELIVERABLES

From our structural analysis services the client should expect the following key deliverables:

- Quick and reliable (re-) orientation of all tectonic and sedimentary structures acquired along with:
- Real time database creation and delivery of preliminary graphic outputs, such as dipmeter logs and others;
- Elaboration of all required graphic outputs including dipmeter logs, rosette diagrams, stereonet plots and other specific diagrams, shortly after data acquisition;
- Characterization of natural fracture connectivity by using information about fracture orientation, length, opening, thickness and density;
- Reliable orientation of stress-related induced fractures based on the full use and integration of well deviation data in relation to the formation features. This allows the determination of the following:
    - Relation with in-situ horizontal stress;
    - Relation between induced and natural fractures;
    - Preferred hydro fracture direction.
- **Composite structural log** with integration of all available logs;
- **Integration of directly acquired core data and fracture description analysis with image logs** in order to assist and calibrate the first before any interpretation;
- **Comprehensive structural geology study** with reference to the main deformation stages, mechanisms and timing and integration within the regional geology of the study area;
- **Fracture porosity and permeability** calculation from collected core data (the detailed methodology with examples is available on requirement);
- **Prediction of the optimal drilling direction** from oriented cores in order to maximize reservoir performance;
- **Continuous high-resolution image log** together with detailed images of the acquired features.
- **Comprehensive and fully detailed digital database**.

6. REGIONAL INTEGRATION (OPTIONAL)

Integration of micro-tectonic results with sedimentological and/or existing structural models is possible on requirement as well as correlation with surrounding wells or any pre-existing structural framework, including:

- Relative contribution to permeability of different structure sets and associated preferential fluid flow vectors;
- Understanding of the relationship between fracture fillings, dissolution processes and available diagenetic evolution;
- Deduction of paleo-stress axis based on slickenside and other features observed within fault planes.