The Ordovician Glaciation in Saudi Arabia — Exploration Challenges Part 2: Geophysics*

Ashraf Khalil[1], Geoffrey Pike[1], Pieter Van Mastrigt[1], and John Smale[2]

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Posted May 14, 2009

*Adapted from oral presentation at AAPG International Conference and Exhibition, Cape Town, South Africa, October 26-29, 2008.

See Part 1 - Search and Discovery article #50175, Moscariello, A., P. Spaak, A. Jourdan, and A-H Azzouni, The Ordovician Glaciation in Saudi Arabia – Exploration Challenges, Part 1: Geology (Outcrop, Subsurface, Analogues).

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Abstract

Extensive post-well geophysical studies have been utilized in support of ongoing seismic interpretation to address recent well results and the overall prospectivity of Ordovician glacial sediments in the South Rub Al Khali Basin. The interface at the base of the Silurian Qusaiba Shale and the top of the Ordovician reservoirs reflects the combination of structuration and paleo-topography caused by glacial erosion during Late Ordovician time and hence cannot be fully described by picking timelines on the seismic data. The presence of seismic multiples and a limited impedance contrast between the Sarah (peri-glacial) and Qasim Formation (pre-glacial) sediments hinders the recognition of the base glacial unconformity on seismic.

Integrated geophysical technologies deployed in the exploration effort include airborne and land-based gravity, high-resolution magnetic data, passive low-frequency seismic, magneto-telluric, multi-azimuth VSP and acoustic impedance data.

Seismic interpretation suggests that the glacial sedimentary succession drapes much of the study area and points to overfill depositional models. Internal sedimentary architecture may consist of nested incised valleys within a broader incised valley. Field analogs suggest that glacial incisions are common, often resulting in a complex architecture of buried hills and adjacent glacial valley systems. Such topographic features and valleys appear to be influenced by the regional basement structural features.

Constrained depth inversion of potential field data has been used to determine if the glacial deposits, rich in diamictites and possibly having a unique density and/or magnetic susceptibility contrast, can be identified and mapped regionally. The combined results of this study helped explain exploration well results and aided the development of more accurate play maps to focus future exploration campaign.

The Ordovician Glaciation in Saudi Arabia

Exploration Challenges Part 2: Geophysics

by

Ashraf Khalil[1], Geoff Pike[1], Pieter Van Mastrigt[1], John Smale[2]

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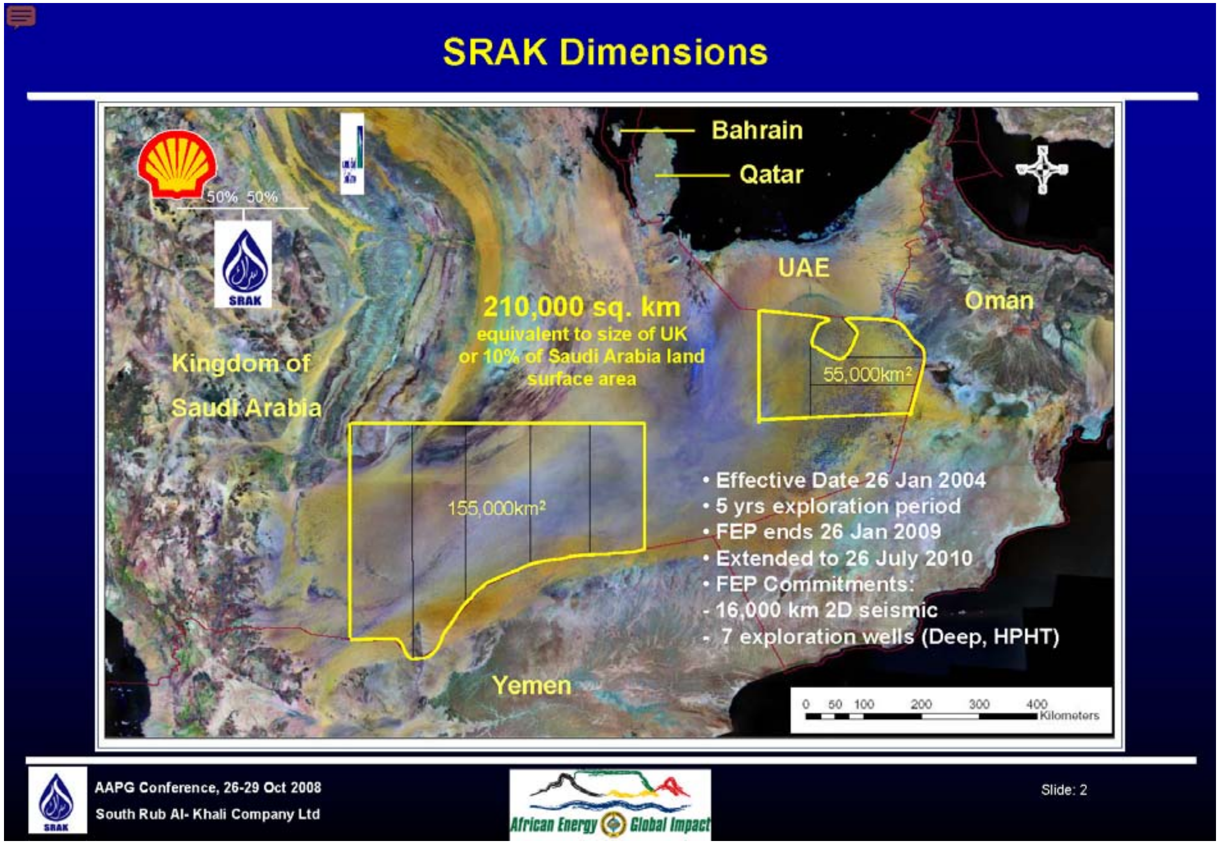

SRAK Dimensions

210,000 sq. km
equivalent to size of UK or 10% of Saudi Arabia land surface area

- Effective Date 26 Jan 2004
- 5 yrs exploration period
- FEP ends 26 Jan 2009
- Extended to 26 July 2010
- FEP Commitments:
  - 16,000 km 2D seismic
  - 7 exploration wells (Deep, HPHT)

AAPG Conference, 26-29 Oct 2008
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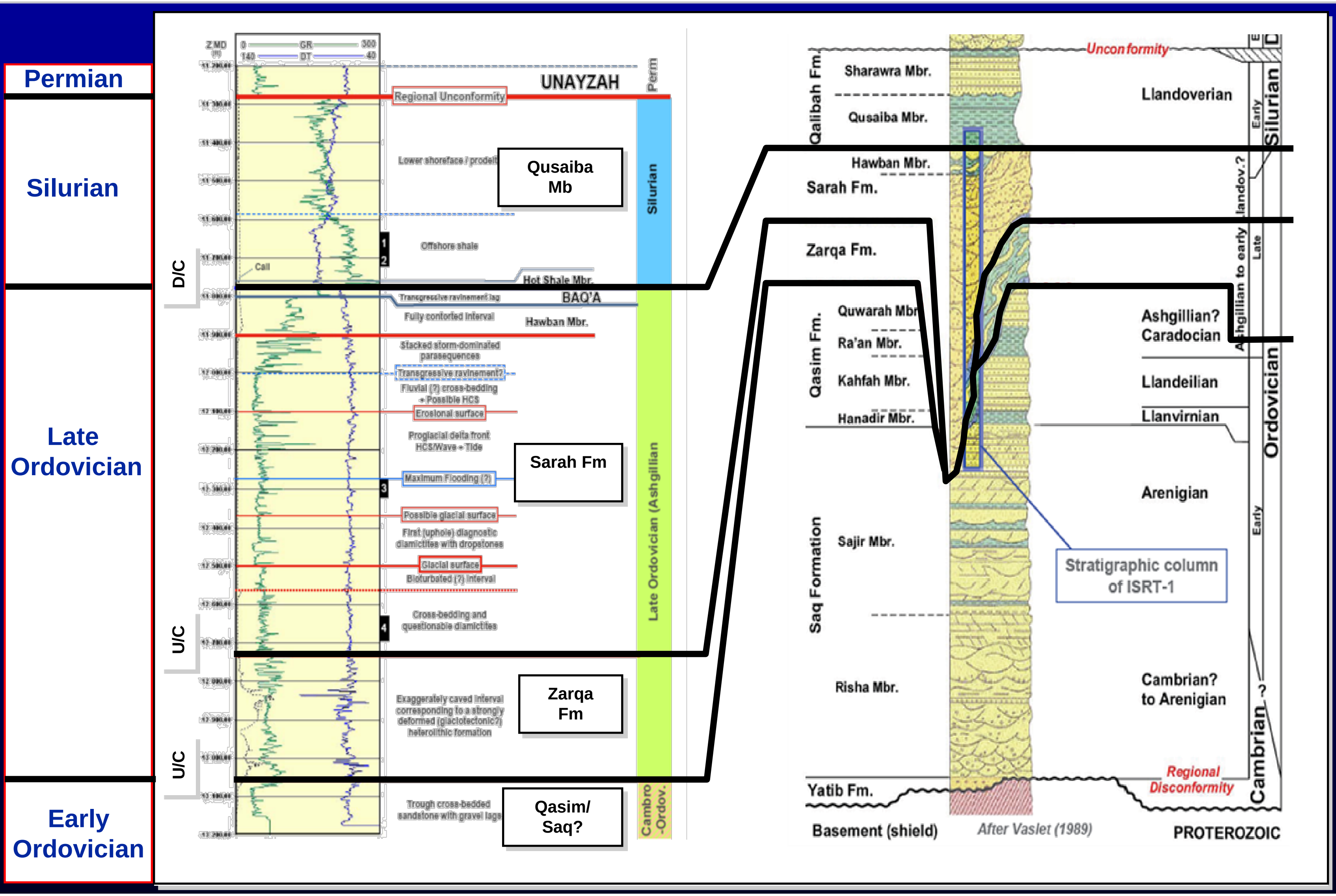
Notes by Presenter:
SRAK's Contract Areas cover **209,160 km2**, equivalent to 10% of the land surface area of Saudi Arabia.

The SRAK Contract Areas are located in the southern part of the Kingdom of Saudi Arabia and cover a large part of the South Rub Al-Khali Basin.

The exploration area is split into two groups of blocks, **Contract Area 1** (Blocks 82-85, 55,000km2) that borders the UAE to the north and Oman to the east and **Contract Area 2** (Blocks 5-9, 155,000km2) that borders Yemen to the south.

3 wells (ISRT-1, MRTN-1, SERJ-1) have been drilled to date in CA2, one well (KIDN-6) is due to spud next month in CA1.

Geological Settings and Palaeozoic Targets in Contract Area 2



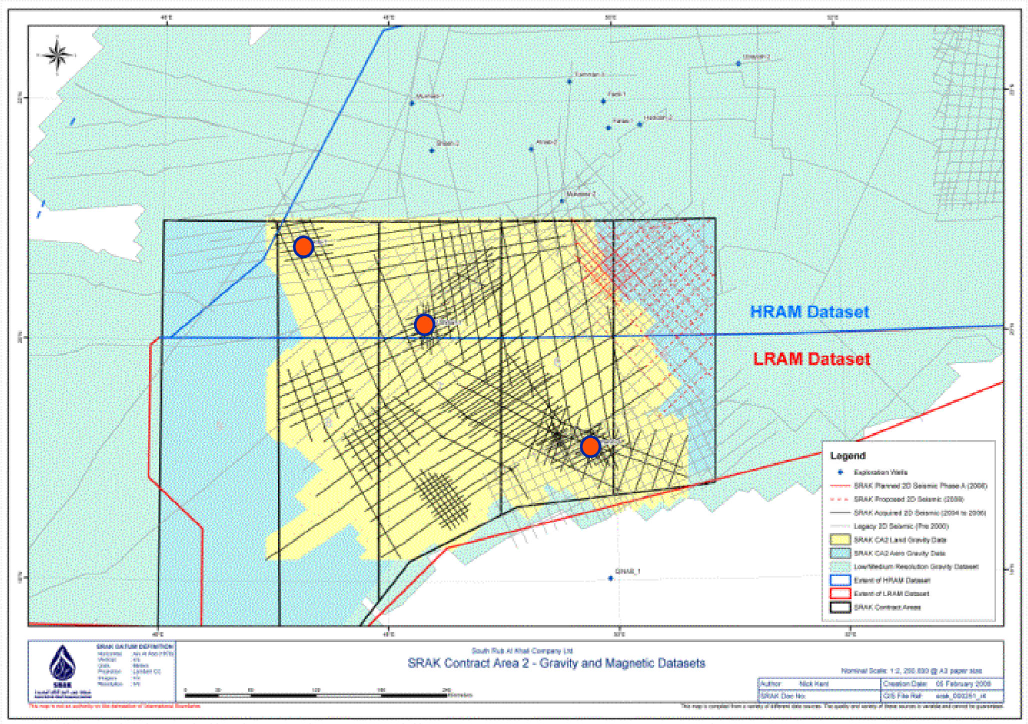
Datasets

Geological and petrophysical datasets

3 (SRAK) drilled wells including 7 Palaeozoic cores	ISRT-1, MRTN-1, SERJ-1
Full suite of logs over the Palaeozoic interval in all SRAK wells	
Image logs over the Palaeozoic interval (ISRT-1)	
4 analogue wells from north of Contract Area 2	MKSR-1, UBYL-2, TKMN-3, HDDH-2
Ordovician outcrops in Saudi Arabia	
Analogue systems (outcrop, drilled prospects and producing fields) in North Africa	

Geophysical

- Regional airborne gravity survey (210,000 km^2)
- 2004 airborne gravity survey (145,000 line km)
- 2D line seismic data, gravity and up-hole data
- 1988 Aramco airborne magnetic survey
- 2004 SRAK / Aramco HRAM*
- Magneto-Telluric Recording (125 stations)
- Low Frequency Seismic – 2350 km
- 2D reprocessing of legacy data (28,000 km)



*HRAM = high resolution airborne magnetics

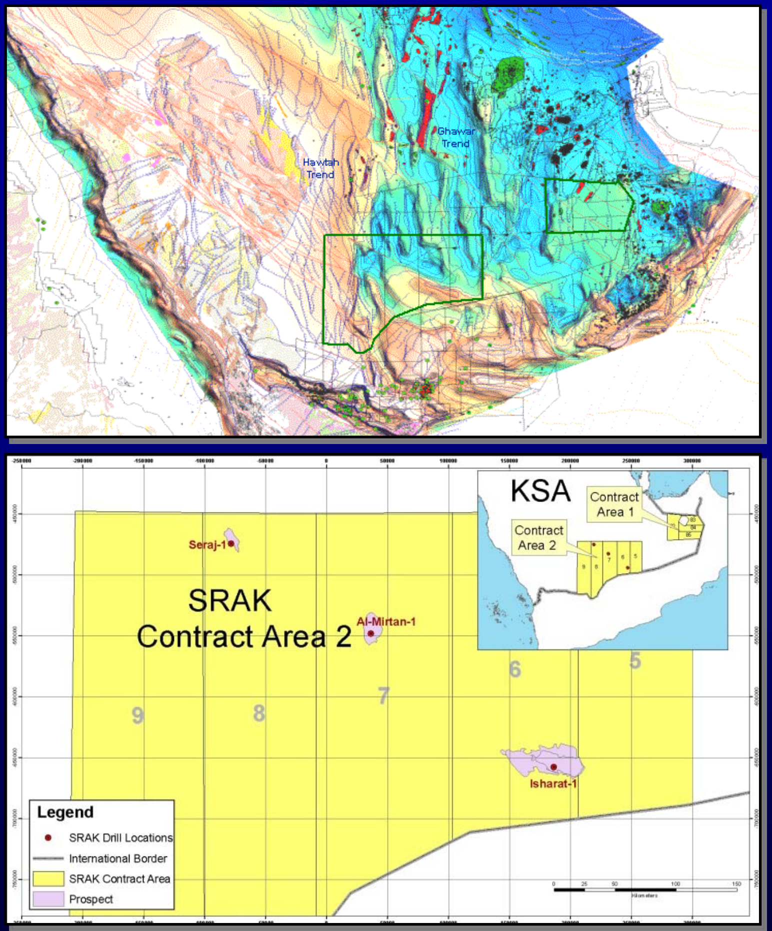
Lower Palaeozoic Glacial System in SRAK’s Contract Area 2

Location

- SRAK’s Contract Area 2 (CA2) 155,000 km^2
- CA2 has been tested by three wells: Isharat-1 (ISRT-1), Al-Mirtan-1 (MRTN-1) and Seraj-1 (SERJ-1)

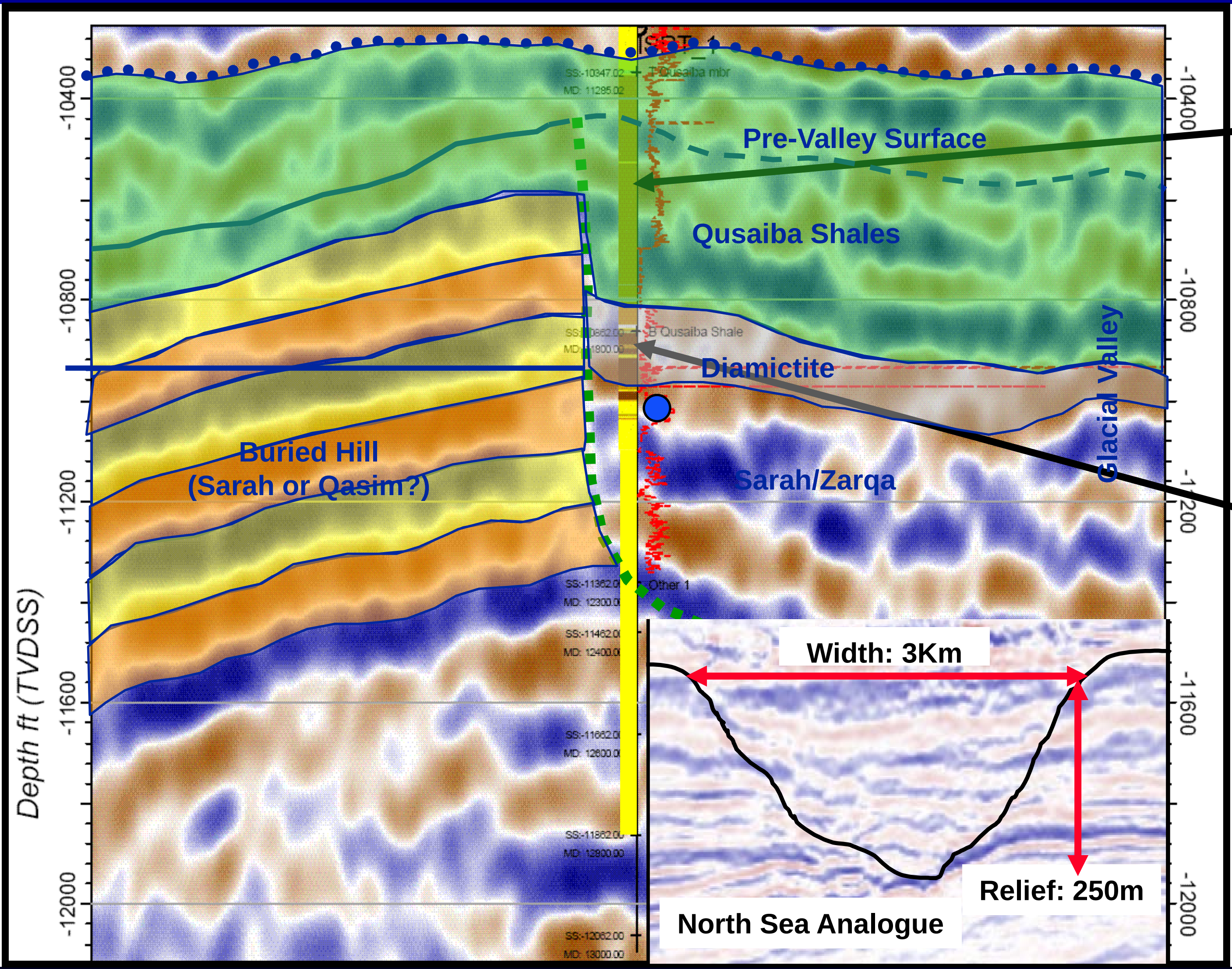
Primary exploration target

- Glacial Ordovician Sarah/ Zarqa sandstones pre-glacial Qasim/ Saq sandstones sealed by post-glacial Qusaiba shales
- The Silurian Qusaiba ‘Hot Shales’ is the source rock requiring downward charge into underlying reservoir



TOP: Basement structure map of Saudi Arabia and environs
Bottom: SRAK’s Contract Area 2 with the first three drilled prospects illustrated (ISRT-1, MRTN-1 and SERJ-1)

Isharat-1 Possible Glacial Valley



Qusaiba Formation

- Thick Qusaiba top seal ~ 400 ft thick
- Increasing **gas shows** with depth (HC diffusion profile)
- Thick (~ 200ft) >200^0 API GR "hot" shale with thin (~30 ft) >300^0 API at base
- Dark shales with abundant graptolites, TOC 1.5-6 % **GOOD SOURCE ROCK**

Objective Sarah/Saq

- Encountered 100 ft diamictites, silty intervals with **fluorescence** in cuttings

- Sarah sands encountered beneath diamictite but **water wet**

- Is this a valid test of a dry structure? **OR**

- Sarah / Qasim host rock (buried hill) has been eroded by glacial valley containing Zarqa sands & diamictites
- large remaining untested closure with significant vertical relief

Geological Models

OVERFILLED MODELS

LAYERCAKE MODEL

Peneplaned Qasim & Saq sandstones overlain by a uniform thickness of Sarah + Qusaiba

PLAY: Structural
MAPPING: Structural maps parallel to Qusaiba-Sarah reflector

OVERFILLED MODEL

Subtle structural relief of Qasim & Saq sandstones entirely buried by Sarah Formation sandstones

PLAY: Structural (with variability in reservoir quality)
MAPPING: Structural maps parallel to Qusaiba-Sarah reflector

UNDERFILLED MODELS

UNDERFILLED MODEL

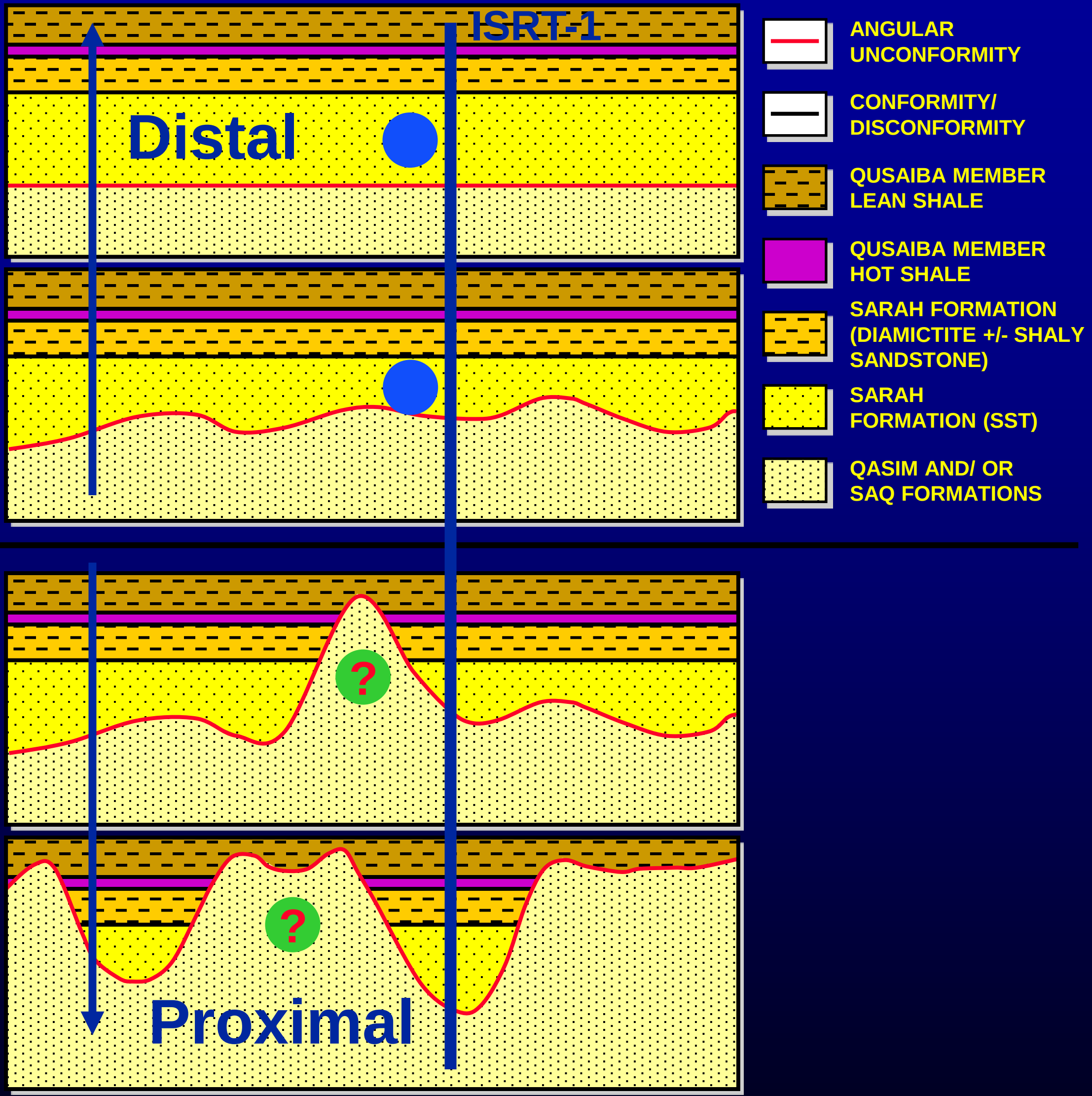
Isolated Qasim & Saq sandstone highs largely buried by thick Sarah Formation sandstones + Qusaiba Member shales

PLAY: Structural with stratigraphic leak points
MAPPING: Structural + seismic facies

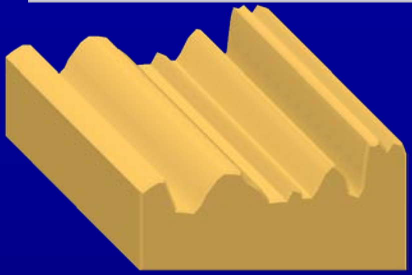
BURIED HILL MODEL

Sarah Formation restricted to valley-fill within glacial canyons with topography finally buried by the end of the Qusaiba flood

PLAY: Structural + Stratigraphic
MAPPING: Map distinct seismic facies (chaotic, parallel etc.)

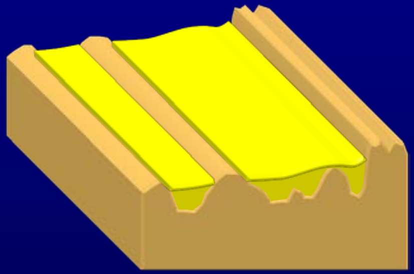


Possibility of a Buried Hill Play in CA2 (Murzuq Basin Analogue)



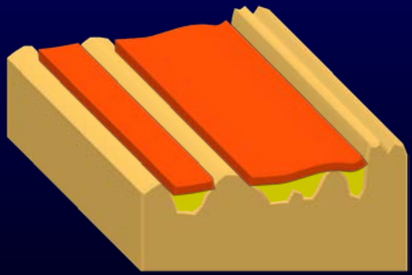
Ashgillian?

- Erosion of Early Ordovician sediments by a glacial event



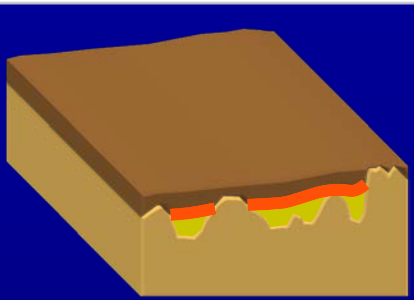
Ashgillian

- Deposition of peri / post glacial sediments in the topographic lows
- Interfluves remain exposed



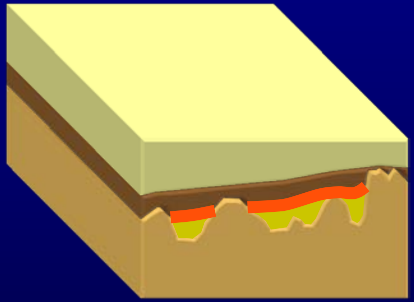
Early Silurian

- Marine Incursion
- Deposition of Basal Qusaiba Hot Shale mbr (Source Rock) in topographic lows



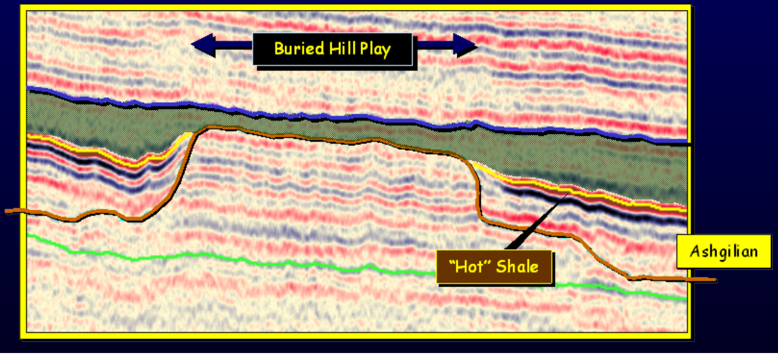
Mid Silurian

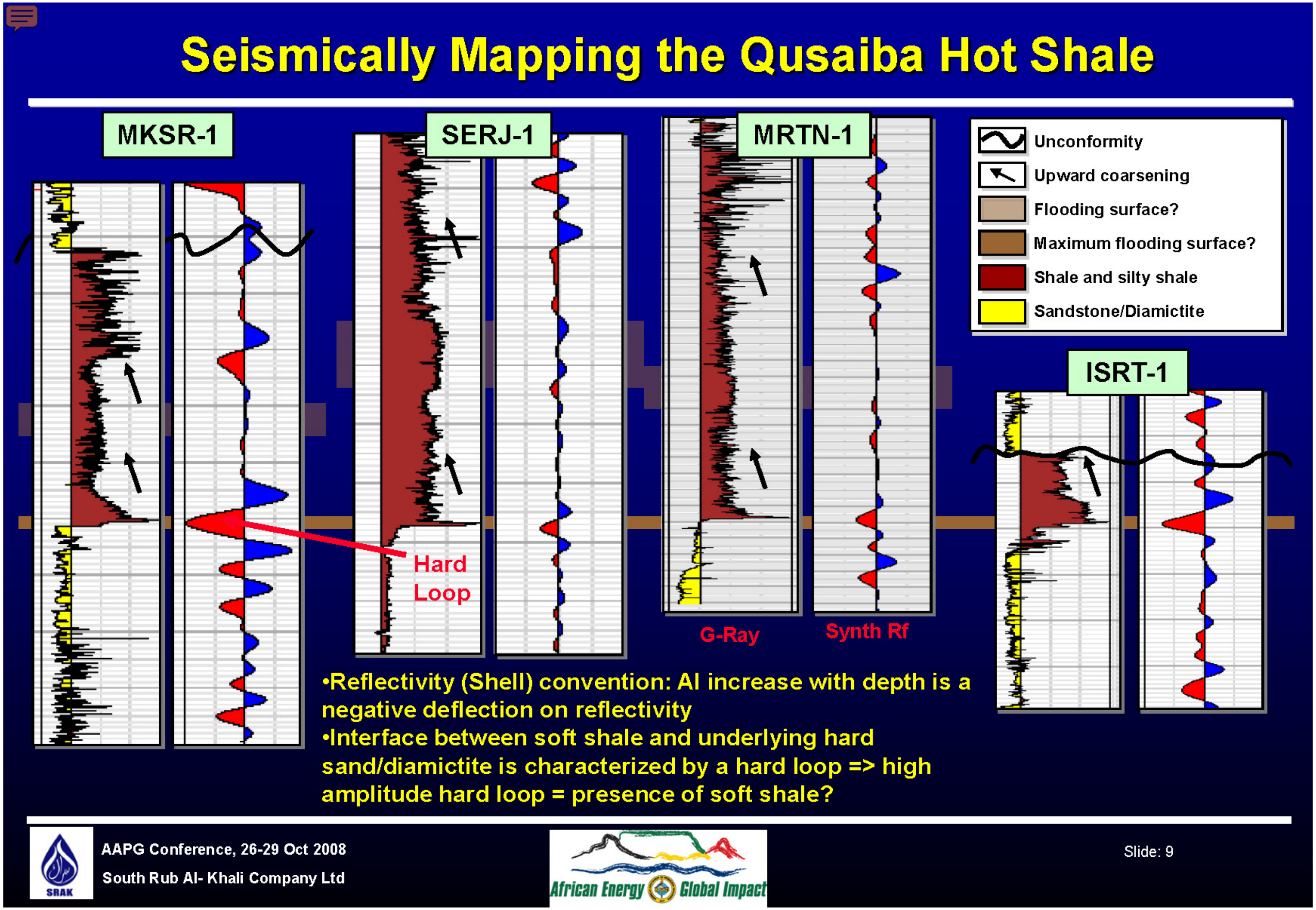
- Marine Incursion continues
- Deposition of remaining Qusaiba Shale mbr draping / infilling most topography



Late Silurian

- Marine Incursion continues
- Deposition of Sharwarah mbr (siltstone) draping / infilling remaining topography





Seismically Mapping the Qusaiba Hot Shale

- ∿ Unconformity
- ↖ Upward coarsening
- ▨ Flooding surface?
- ▨ Maximum flooding surface?
- 🟥 Shale and silty shale
- 🟨 Sandstone/Diamictite

- Reflectivity (Shell) convention: AI increase with depth is a negative deflection on reflectivity
- Interface between soft shale and underlying hard sand/diamictite is characterized by a hard loop => high amplitude hard loop = presence of soft shale?

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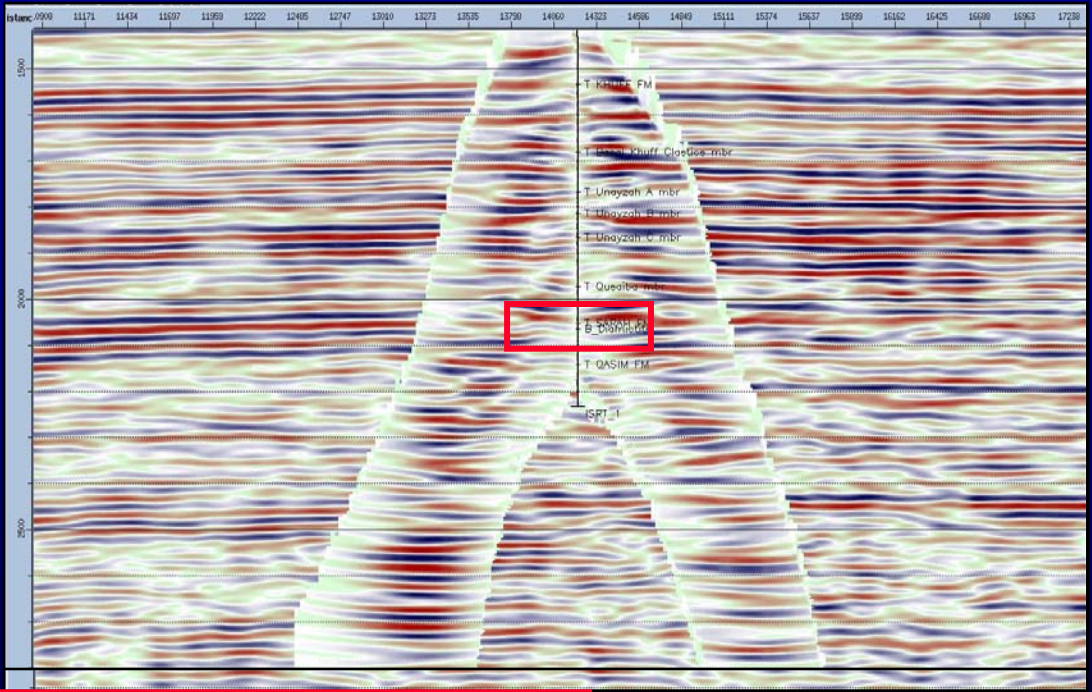
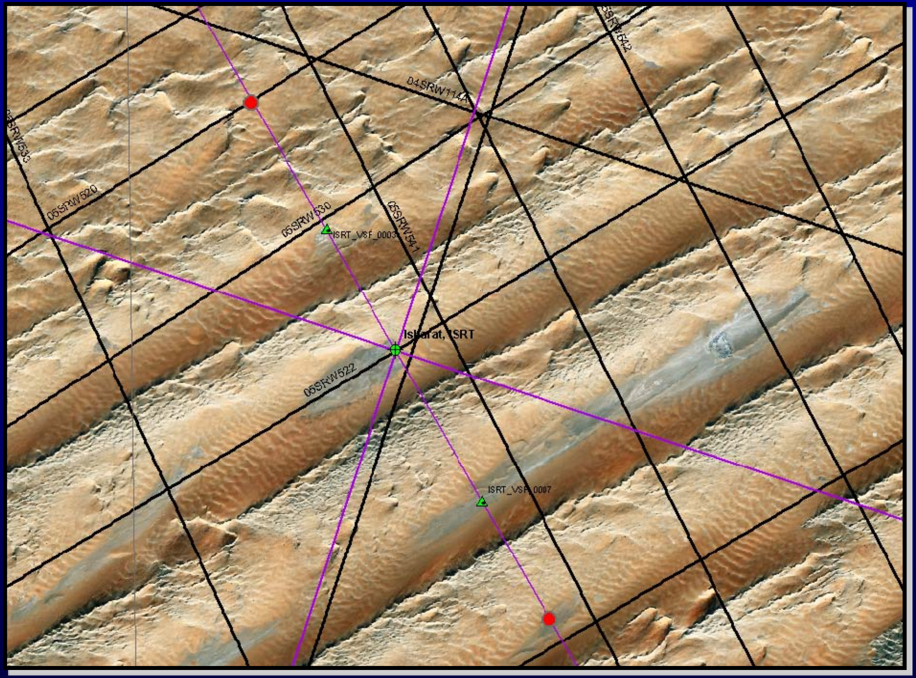
Notes by Presenter: Reflectivity (Shell) convention: AI increase with depth is a negative deflection on reflectivity. Interface between soft shale and underlying hard sand/diamictite is characterized by a hard loop.

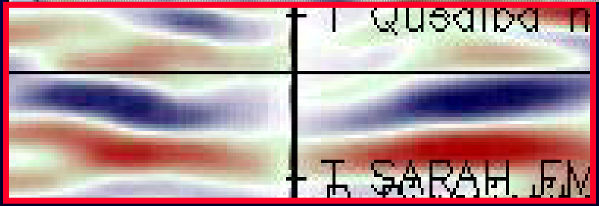
ISRT-1 Multi-azimuth VSP

Objective of Isharat-1 multi-azimuth VSP

- Identify possible presence of valley / buried hill topography
- Identify possible distribution of soft shale (source rock)

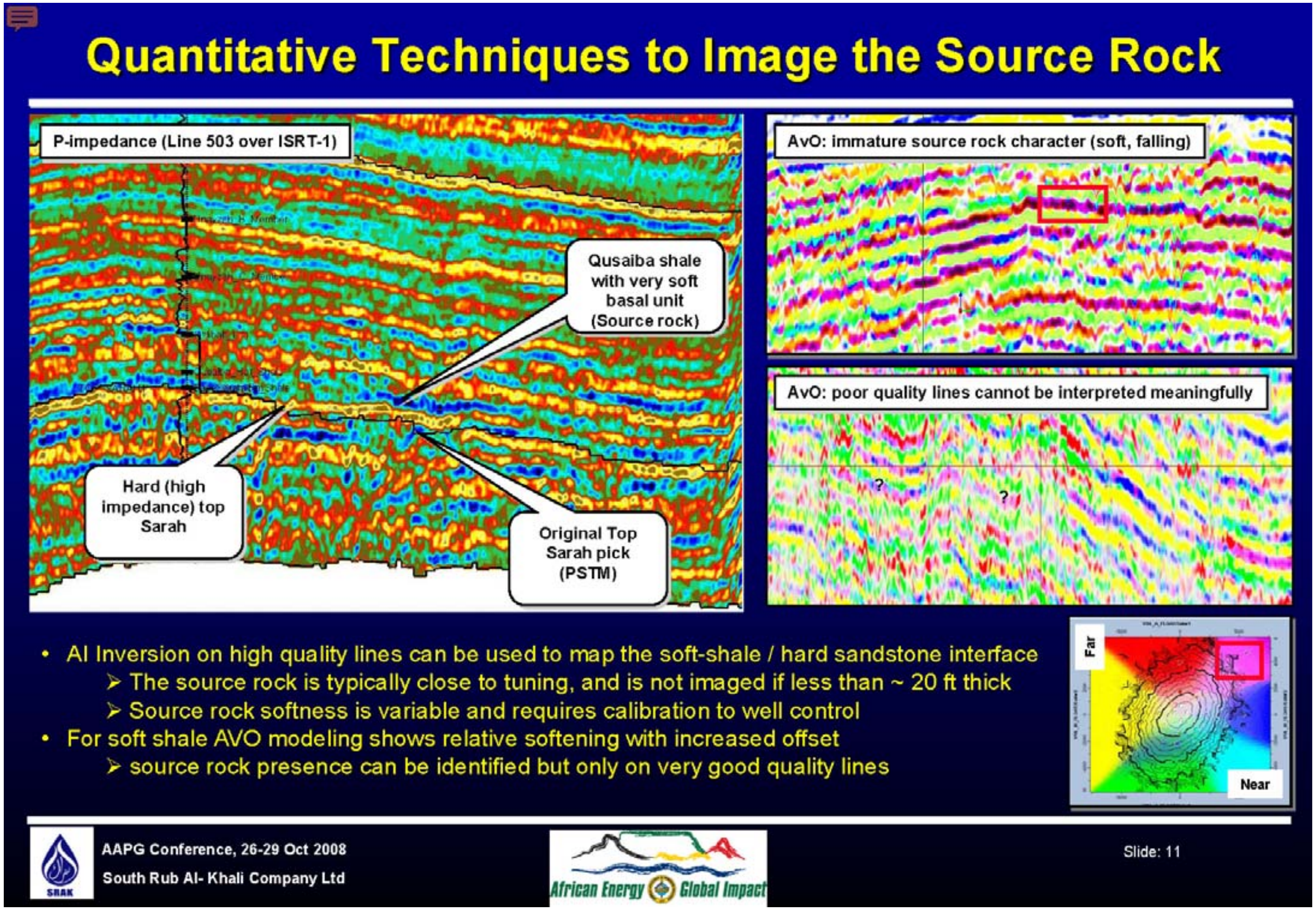






Conclusions

- **Isharat-1 VSP provided extremely good well-to-seismic calibration**
- **Offsets showed limited distribution of soft-hard amplitude response giving apparent support for interpretation as a valley-constrained Hot Shale unit**



Quantitative Techniques to Image the Source Rock

P-impedance (Line 503 over ISRT-1)

Qusaiba shale with very soft basal unit (Source rock)

Hard (high impedance) top Sarah

Original Top Sarah pick (PSTM)

AvO: immature source rock character (soft, falling)

AvO: poor quality lines cannot be interpreted meaningfully

- AI Inversion on high quality lines can be used to map the soft-shale / hard sandstone interface
  - ➢ The source rock is typically close to tuning, and is not imaged if less than ~ 20 ft thick
  - ➢ Source rock softness is variable and requires calibration to well control
- For soft shale AVO modeling shows relative softening with increased offset
  - ➢ source rock presence can be identified but only on very good quality lines

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Notes by Presenter:

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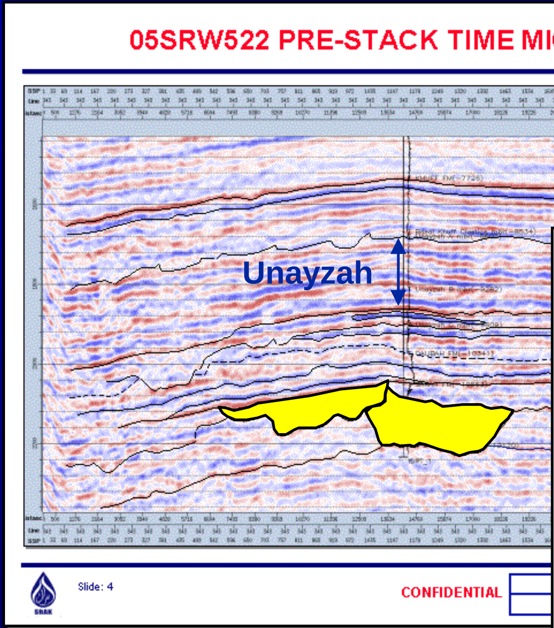
Geophysical Mapping Techniques



05SRW522 PRE-STACK TIME MIGRATION (PSTM)

Time section
This is the PSTM time section with no additional processing or filtering applied

Results

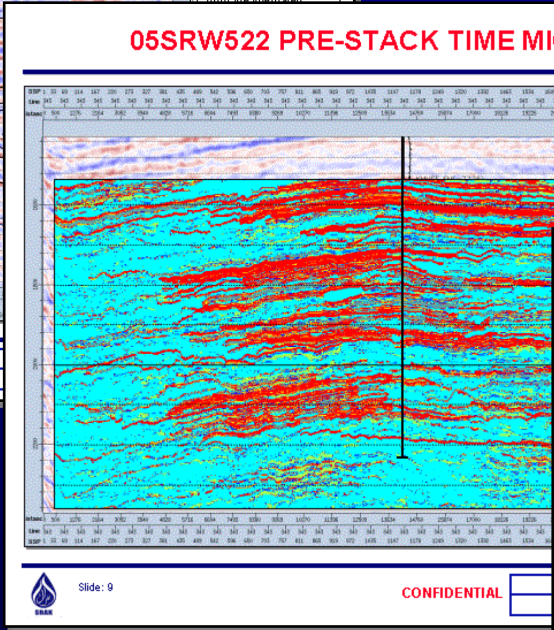
Interpreted lines are from the integrated

Slide: 4

CONFIDENTIAL

CONVENTIONAL INTERPRETATION:
A glacial valley interpretation fits seismic data but suffers from uncertainties such as:

- Contamination from multiples generated in the shallower Unayzah section propagated into the deeper Sarah level
- Bias towards amplitude strength rather than the whole shape of the seismic wavelet
- Can interpretation be automated?



05SRW522 PRE-STACK TIME MIGRATION (PSTM)

Time section
This is the PSTM time section with no additional processing or filtering applied

Results

Interpreted lines are from the integrated

Slide: 9

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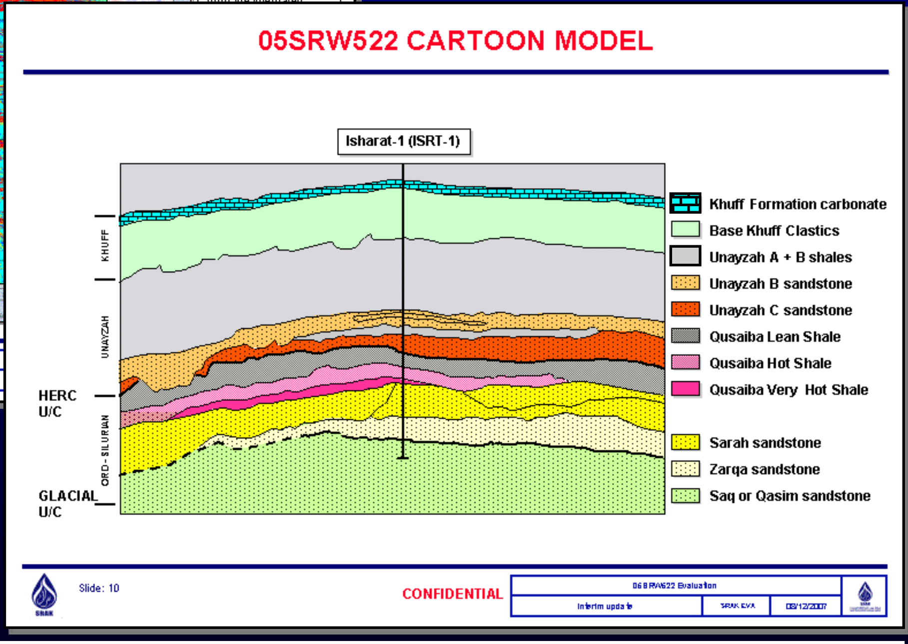
SPECTRAL TECHNIQUES:
Spectral widening and decomposition are used to create seismic subsets that are used to for specific purposes (e.g. multiple identification or unconformity identification, left)



05SRW522 CARTOON MODEL

Isharat-1 (ISRT-1)

▦	Khuff Formation carbonate
🟩	Base Khuff Clastics
☐	Unayzah A + B shales
🟧	Unayzah B sandstone
🟥	Unayzah C sandstone
▨	Qusaiba Lean Shale
▨	Qusaiba Hot Shale
▨	Qusaiba Very Hot Shale
🟨	Sarah sandstone
▨	Zarqa sandstone
🟩	Saq or Qasim sandstone

Slide: 10

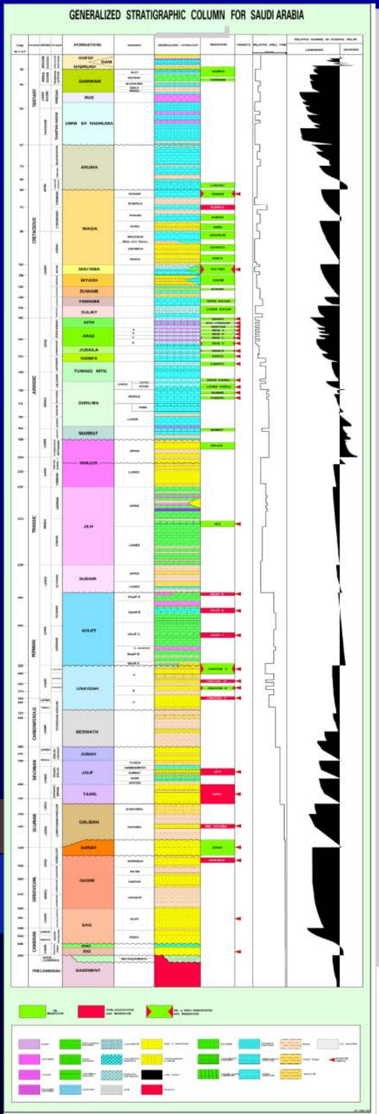
CONFIDENTIAL

06SRW622 Evaluation
Interim update | SRAK EVA | 08/12/2007

TRACE LENGTH:
Trace length is one of the attributes that can be used to classify the seismic. Here, more continuous traces are assigned 'hotter' colours and image continuous features with variable amplitude

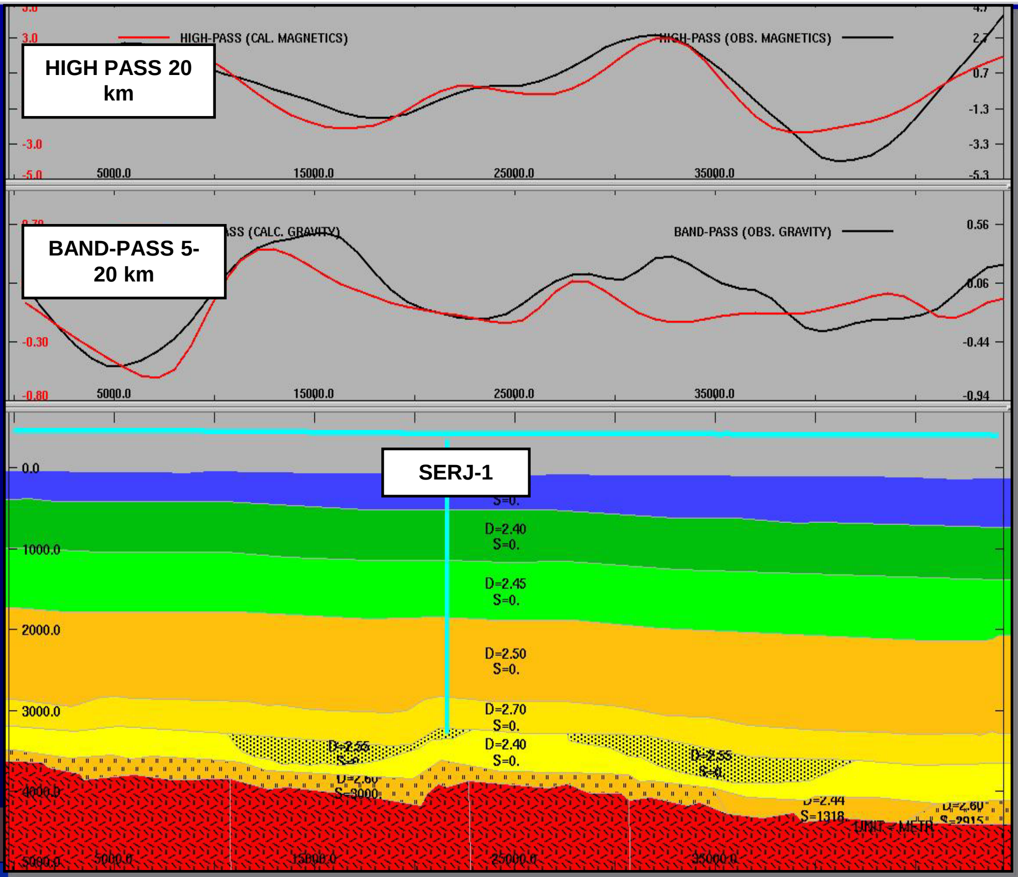
UPDATE TO THE GEOLOGICAL MODEL:
Here, the trace length attribute has been used to better image the base-Sarah glacial unconformity. The original interpretation (essentially layercake geology comprising laterally amalgamated channels) is seen to be robust but subtle features are much better imaged. This line shows very strong evidence that there is no significant glacial topography adjacent to Isharat (in this orientation!).

Gravity and Magnetics to Image Ordovician glacial valleys?



SERJ	MRTN	ISRT	Den	M-Sus
2.2	2.2	2.25		
2.3	2.3	2.4		
2.4	2.4	2.5		
2.7	2.7	2.65		
2.2	2.4	2.6		
2.6	2.5	2.35	**2.5**	**80**
2.5	2.4	2.4	**2.4**	**50**
2.4	2.45	2.45	**2.45**	**50**
2.7	2.65	2.66	**2.68**	**70**
2.55	2.6	2.25	**2.55**	**120** **30**

Measured density (g/cc, left) and magnetic susceptibility values (microcgs, right) from SRAK wells with best-guess averages (bold), diamictite M-sus in red circle

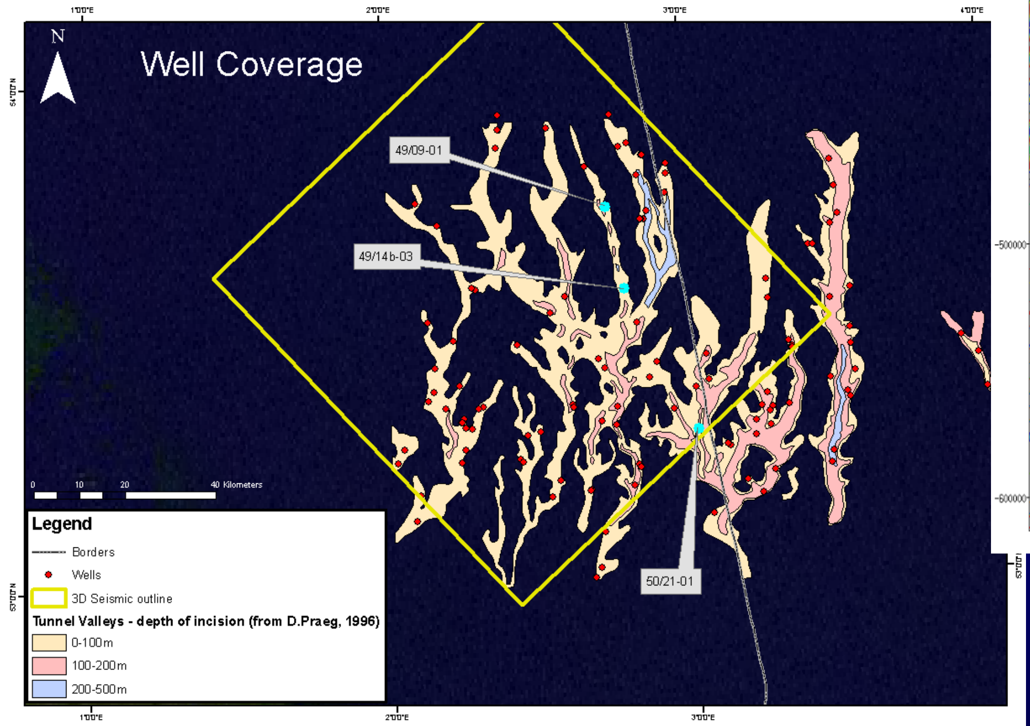


Model shows observed and calculated magnetic (top) and gravity (middle) data over SERJ-1

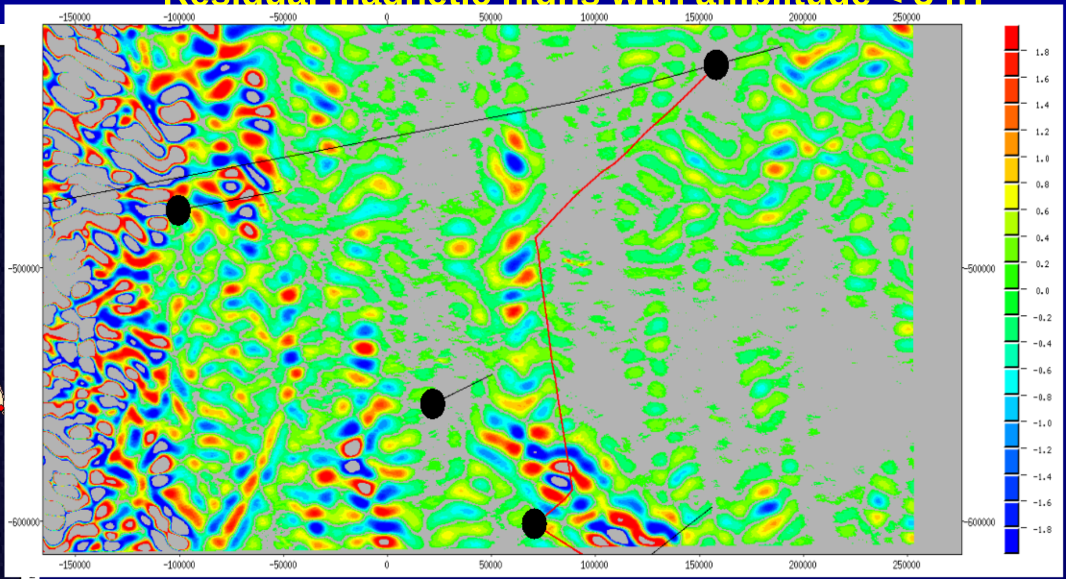
Observed anomalies require valley-fills > 250 m thick of diamictite. This is geologically unlikely as largest valleys at outcrop are c. 300 m thick mostly filled by low susceptibility sandstone rather than high susceptibility diamictite

Gravity and Magnetics to Image Ordovician glacial valleys

North Sea Tunnel Valley Analogue Study 2006



Residual magnetic highs with amplitude < 3 nT



WELL	RESIDUAL MAG	CONFIDENCE	RESIDUAL GRAV	CONFIDENCE
ISRT-1	High (N of well)	Medium (LRAM)	Low	High (land)
MRTN-1	None	High (HRAM)	None	High (Land)
SERJ-1	High	High (HRAM)	Low	High (Land)
MKSR-1	None	High (HRAM)	None	High (SRK)

CONCLUSIONS

Even with excellent quality gravity and magnetic data it is not possible to ‘see’ the architecture of the Ordovician geology because measured gravity and magnetic susceptibility contrasts are too low

Geological Models

OVERFILLED MODELS

LAYERCAKE MODEL

Peneplaned Qasim & Saq sandstones overlain by a uniform thickness of Sarah + Qusaiba

PLAY: Structural
MAPPING: Structural maps parallel to Qusaiba-Sarah reflector

OVERFILLED MODEL

Subtle structural relief of Qasim & Saq sandstones entirely buried by Sarah Formation sandstones

PLAY: Structural (with variability in reservoir quality)
MAPPING: Structural maps parallel to Qusaiba-Sarah reflector

UNDERFILLED MODELS

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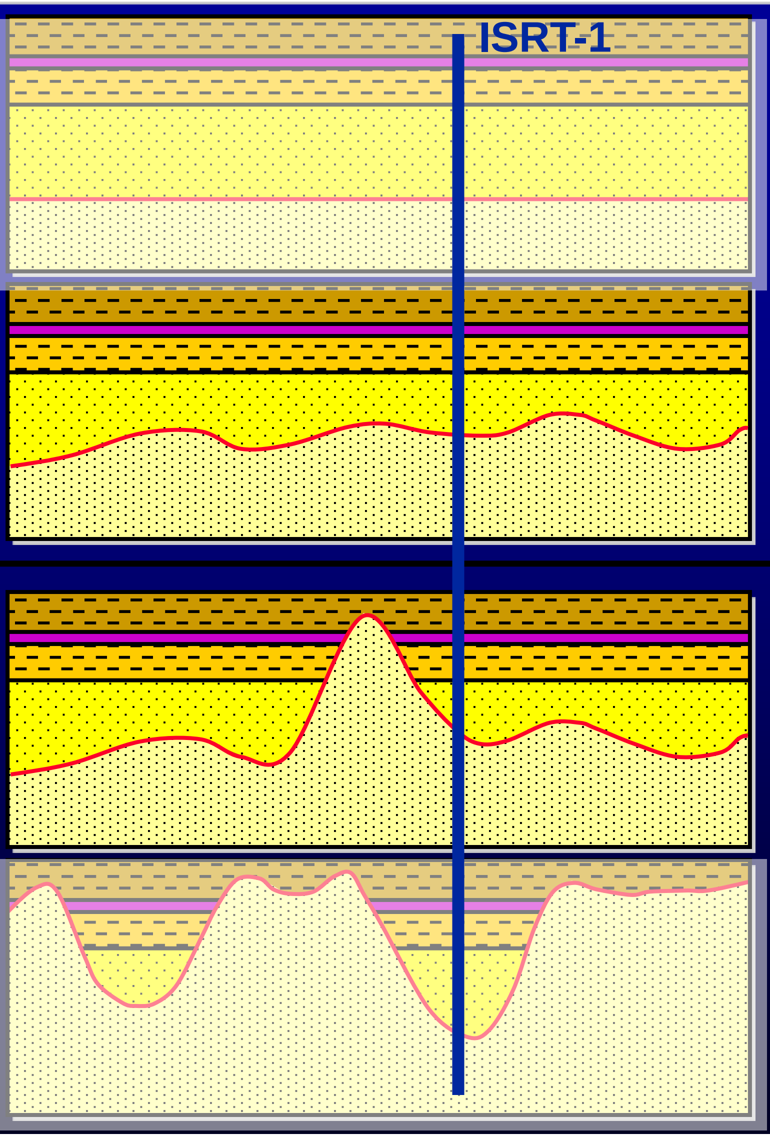
Isolated Qasim & Saq sandstone highs largely buried by thick Sarah Formation sandstones + Qusaiba Member shales

PLAY: Structural with stratigraphic leak points
MAPPING: Structural + seismic facies

BURIED HILL MODEL

Sarah Formation restricted to valley-fill within glacial canyons with topography finally buried by the end of the Qusaiba flood

PLAY: Structural + Stratigraphic
MAPPING: Map distinct seismic facies (chaotic, parallel etc.)



- — ANGULAR UNCONFORMITY
- — CONFORMITY/ DISCONFORMITY
- ▨ QUSAIBA MEMBER LEAN SHALE
- ■ QUSAIBA MEMBER HOT SHALE
- ▨ SARAH FORMATION (DIAMICTITE +/- SHALY SANDSTONE)
- ▦ SARAH FORMATION (SST)
- ▦ QASIM AND/ OR SAQ FORMATIONS

CONCLUSIONS

The Sarah Formation appears to have effectively filled any glacial topography prior to the 'Silurian Flood' although rare basement highs may be preserved and would be interesting prospects

Conclusions

Lower Palaeozoic Stratigraphy

- The Ordovician Sarah formation represents glaciogenic sandstones with a strong marine influence
- In SRAK CA2 glacial incisions into older (Qasim / Saq) sandstones appear to have been (largely?) buried by the Sarah outwash deposits
- Above the Sarah the Hawban Formation records a major phase of melting with deposition of a thick diamictite
- The Top Hawban diamictite appears to form a seal hindering effective downward charge
- The overlying ‘Silurian Flood’ deposited ‘Hot Shale’ (TOC 6%) overlain by shallow water shales (TOC < 1.5%)

What Geophysical Techniques Work?

- The mapping of Ordovician glacial valleys has been attempted using high resolution gravity & magnetic data and a variety of pre and post stack processed and filtered seismic data
- Gravity and magnetic datasets on their own are not able to resolve subtle Lower Palaeozoic features
- Seismic is still the best geophysical exploration tool despite sparse coverage and variable data quality
  - Inversion data identifies the presence of the “soft” source rock but this cannot be distinguished acoustically from other nearby soft features and requires high data quality
  - The presence of the overlying soft Qusaiba shale (SR) can be detected by the increased amplitude of the (hard) top Sarah reflector but again this depends on data quality

- **GEOLOGICAL MODEL IS PRIMARY BUT IS COMPLIMENTED & DE-RISKED BY GEOPHYSICS**

Acknowledgements

We would like to thank our colleagues in SRAK, Shell and Saudi Aramco for their cooperation on this project.

We gratefully acknowledge the contributions from numerous contractors.

Last but not least, we like to thank the KSA Ministry of Petroleum and Mineral Resources for their continued support and permission to present this paper.

...Rub Al-Khali 440 Ma ago

"The changing Arctic"
PHYSICS TODAY
August 2004

Rub Al-Khali Present Day...

SRAK

South Rub Al-Khali Company Limited

Shell	**50%**
Saudi Aramco	**50%**