A Geologic Review of the Mahogany Subsalt Discovery: A Well That Proved a Play*
(The Mahogany Subsalt Discovery: A Unique Hydrocarbon Play, Offshore Louisiana**)

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Abstract

The Mahogany subsalt discovery of Phillips Petroleum Company, in partnership with Anadarko Petroleum Corporation and Amoco Production Company, is the petroleum industry's first commercial subsalt oil development in the Gulf of Mexico. Located 80 miles offshore Louisiana on Ship Shoal Blocks 349 and 359, the Mahogany #1 (OCS-G-12008) was drilled in 375 ft of water to a depth of 16,500 ft and tested both oil and gas below an allochthonous salt sheet. The discovery well tested 7256 BOPD and 7.3 MMCFD on a 32/64" choke at 7063 PSI flowing tubing pressure (FTP). The #2 delineation well (OCS-G-12008) was drilled from the same surface location to a depth of 19,101 ft MD (18,572 ft TVD). A different zone in this well was tested in July, 1994, and flowed 4366 BO and 5.315 MMCFD on a 20/64" choke at 6287 PSI FTP. These flow rates suggest that high sustainable production rates can be expected, and they are confirmed by rock property studies and detailed well log analysis. A third well (OCS-G-12010 #2) was spud in September, 1994.

The primary subsalt reservoir is a high-pressured oil sand with high permeability and porosity and has tremendous deliverability. The field is located 80 miles offshore Louisiana on Ship Shoal South Additions blocks 349/359. The structure is interpreted as a faulted anticline overlain by allochthonous salt. Prestack depth-migrated 3-D seismic data was integrated into a regional geologic model that was based on 2-D time-migrated data. Regionally, the area is characterized by multiple salt sheets, which form a salt canopy sutured east of Mahogany, and several older and deeper sheets are also identified. Structural and rheological aspects of the thick salt sill have been addressed using selected examples of rotary sidewall cores and data on an anomalous "gumbo" shale immediately below the salt which contributes to the understanding of lateral variations at the base of the allochthonous salt.

Subsalt depositional fairways can be approximated by mapping relative salt-induced paleo-bathymetry. Deepwater sand fairways are closely related to salt movements and extend under the salt sheets. Depositional environments and reservoir parameters in productive sandstone intervals have been defined using whole core and well log imaging.

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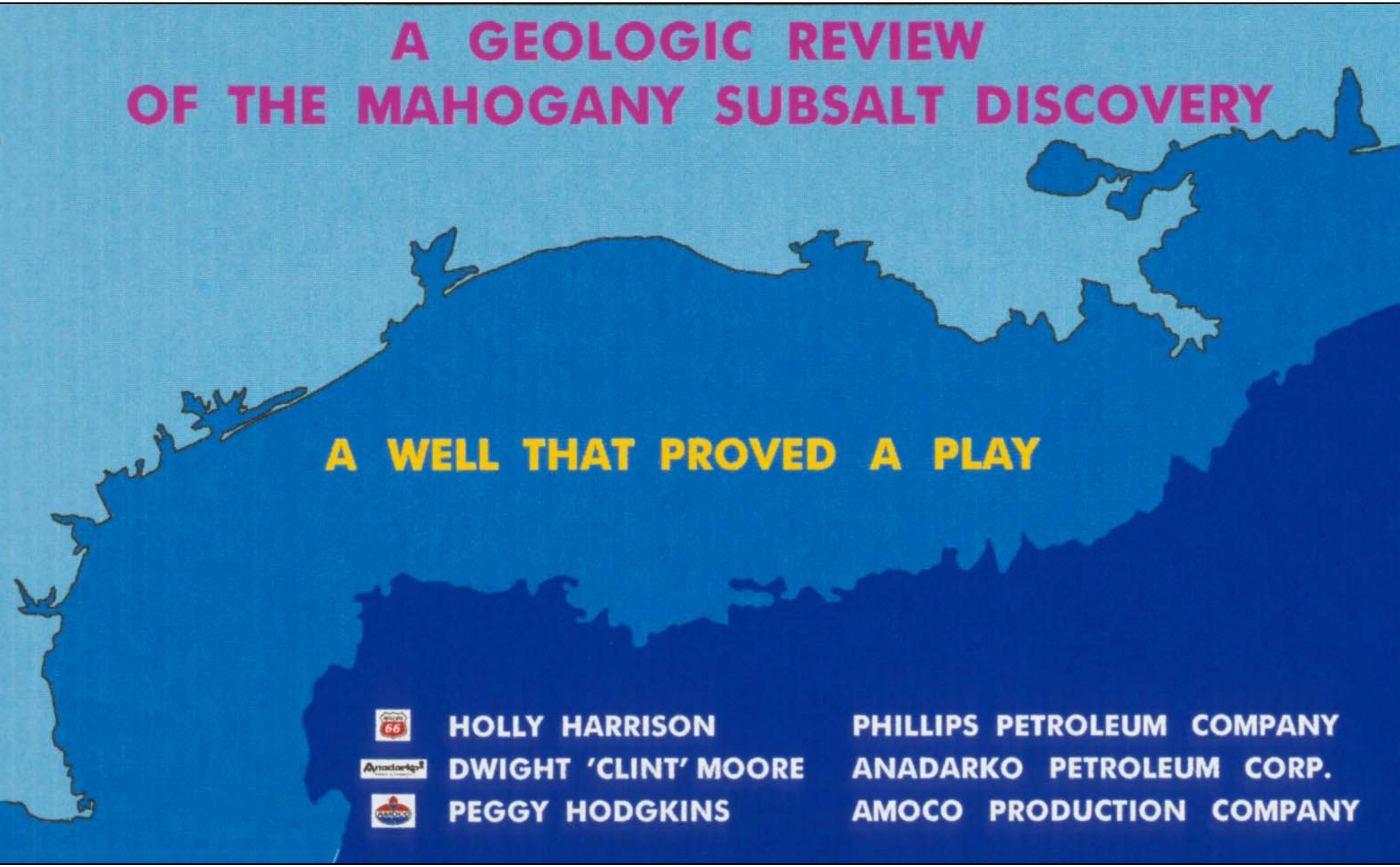

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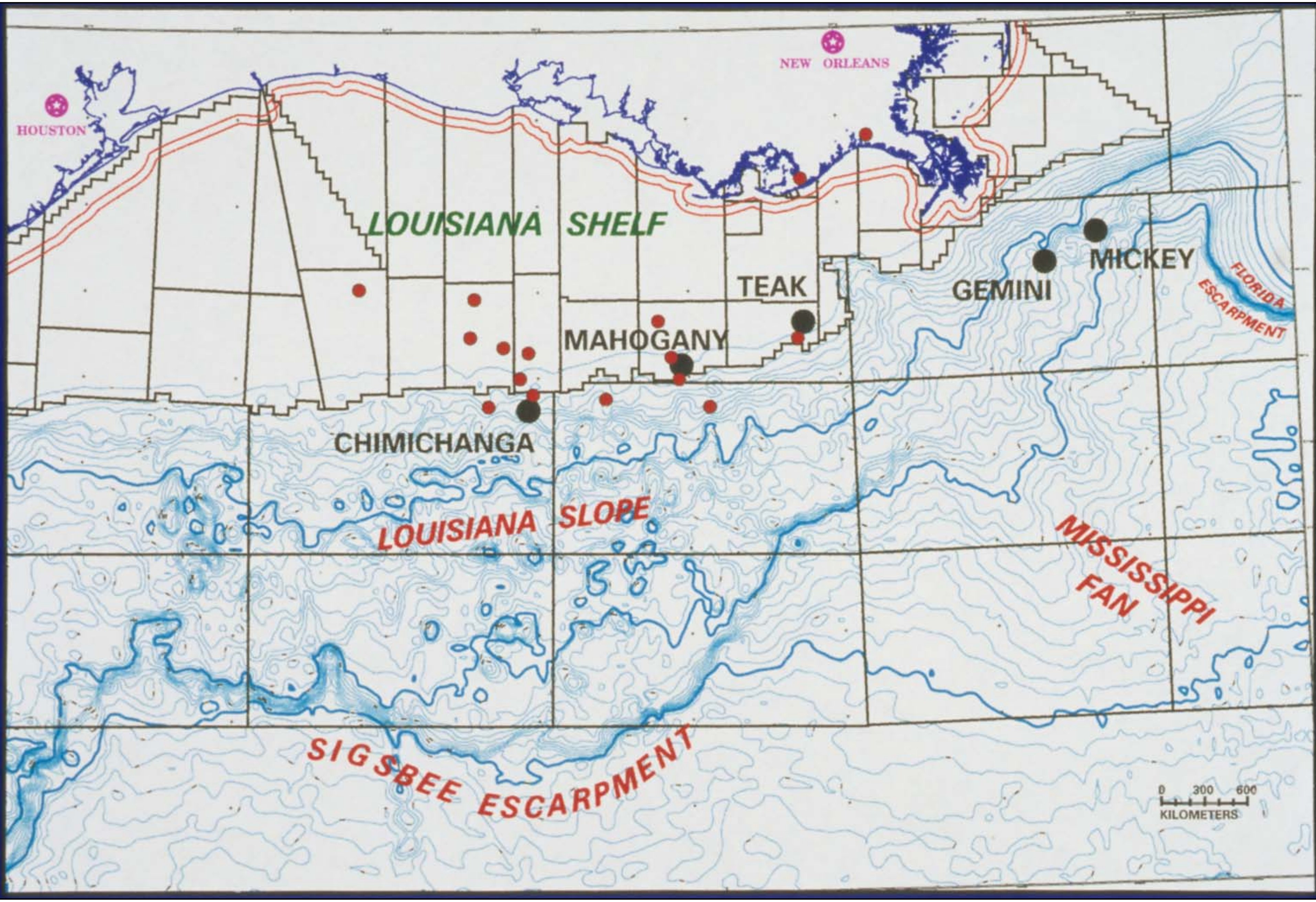

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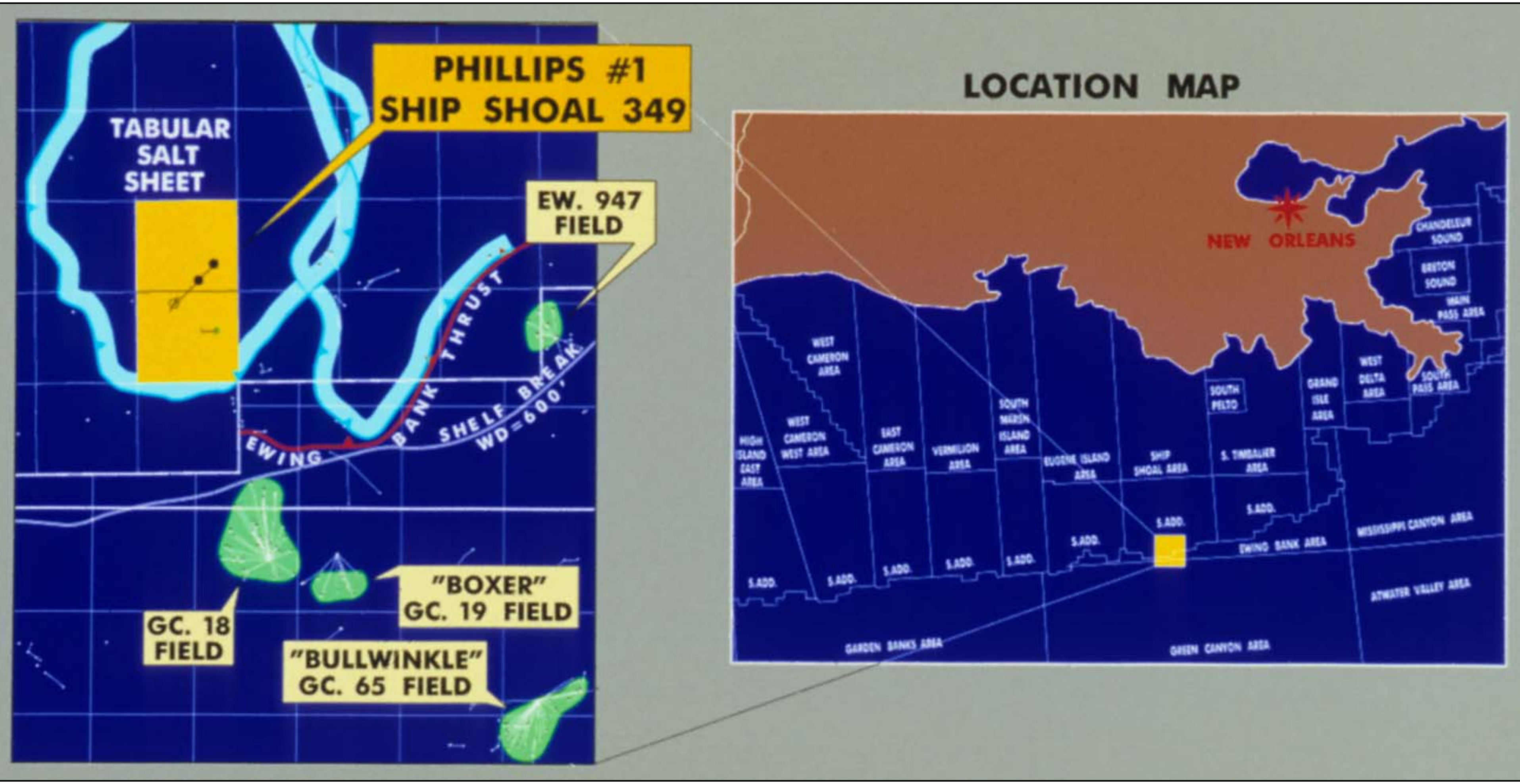

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EXTENT OF SALT SHEETS

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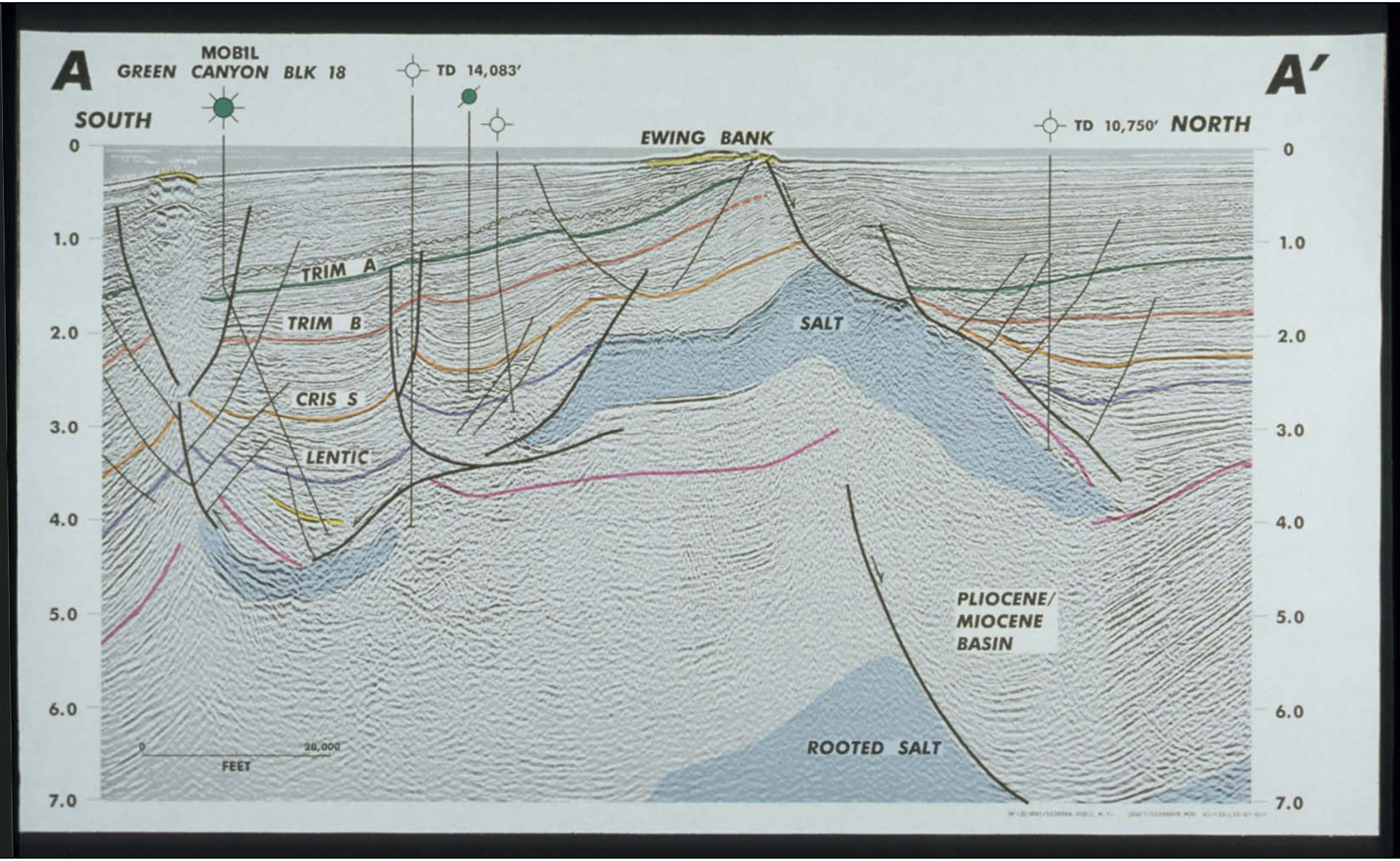

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SUBSALT STRUCTURE

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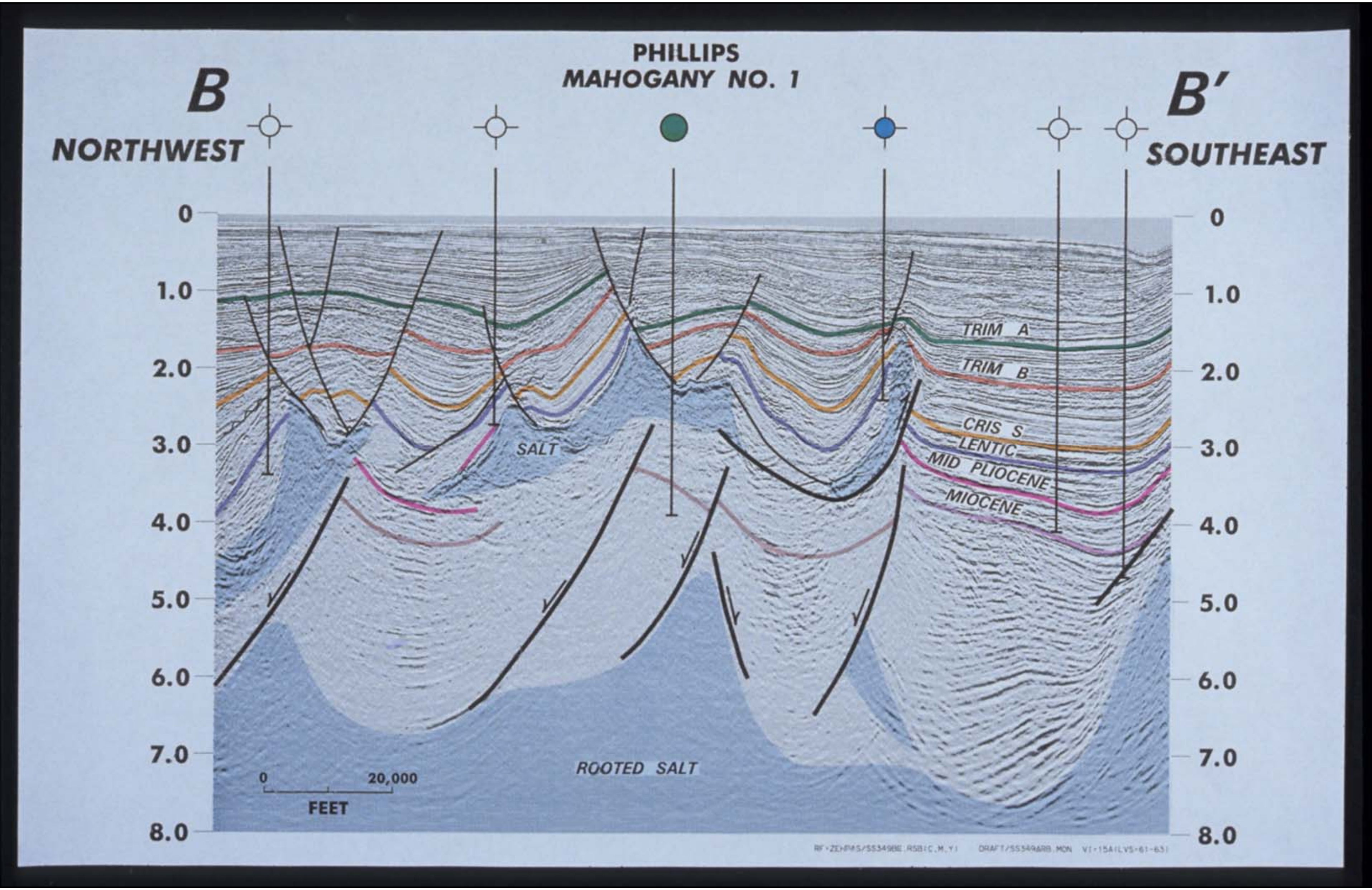

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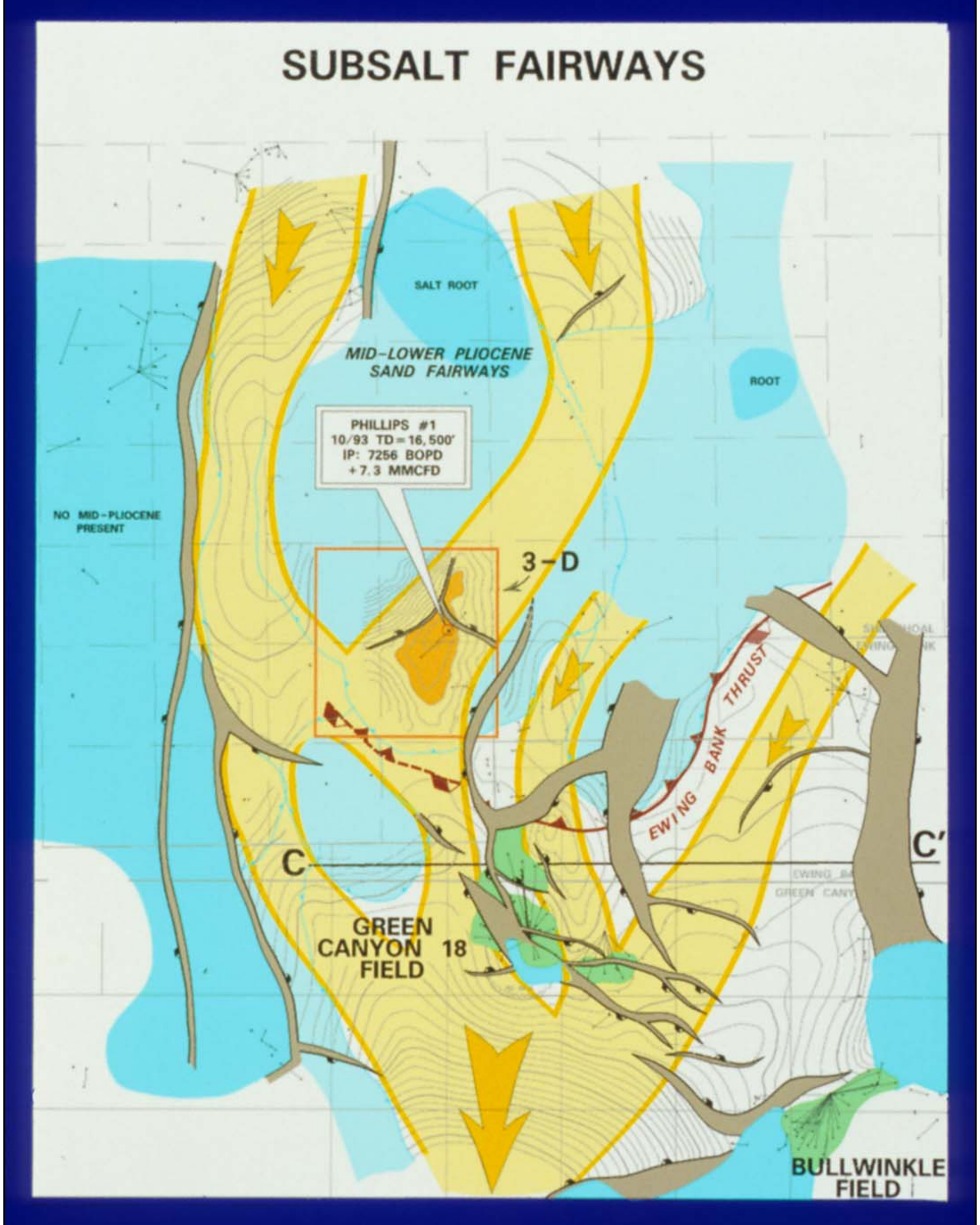

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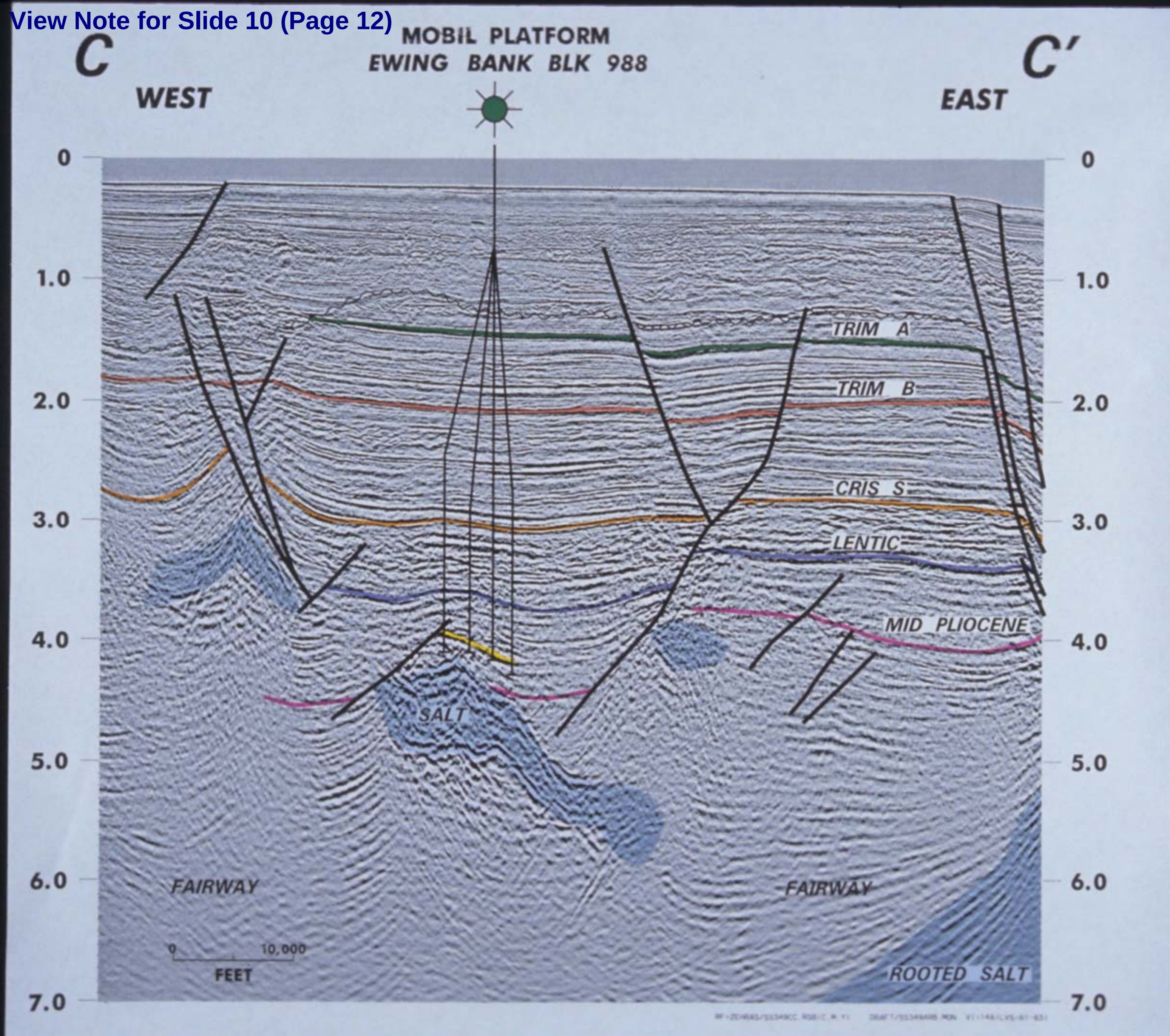

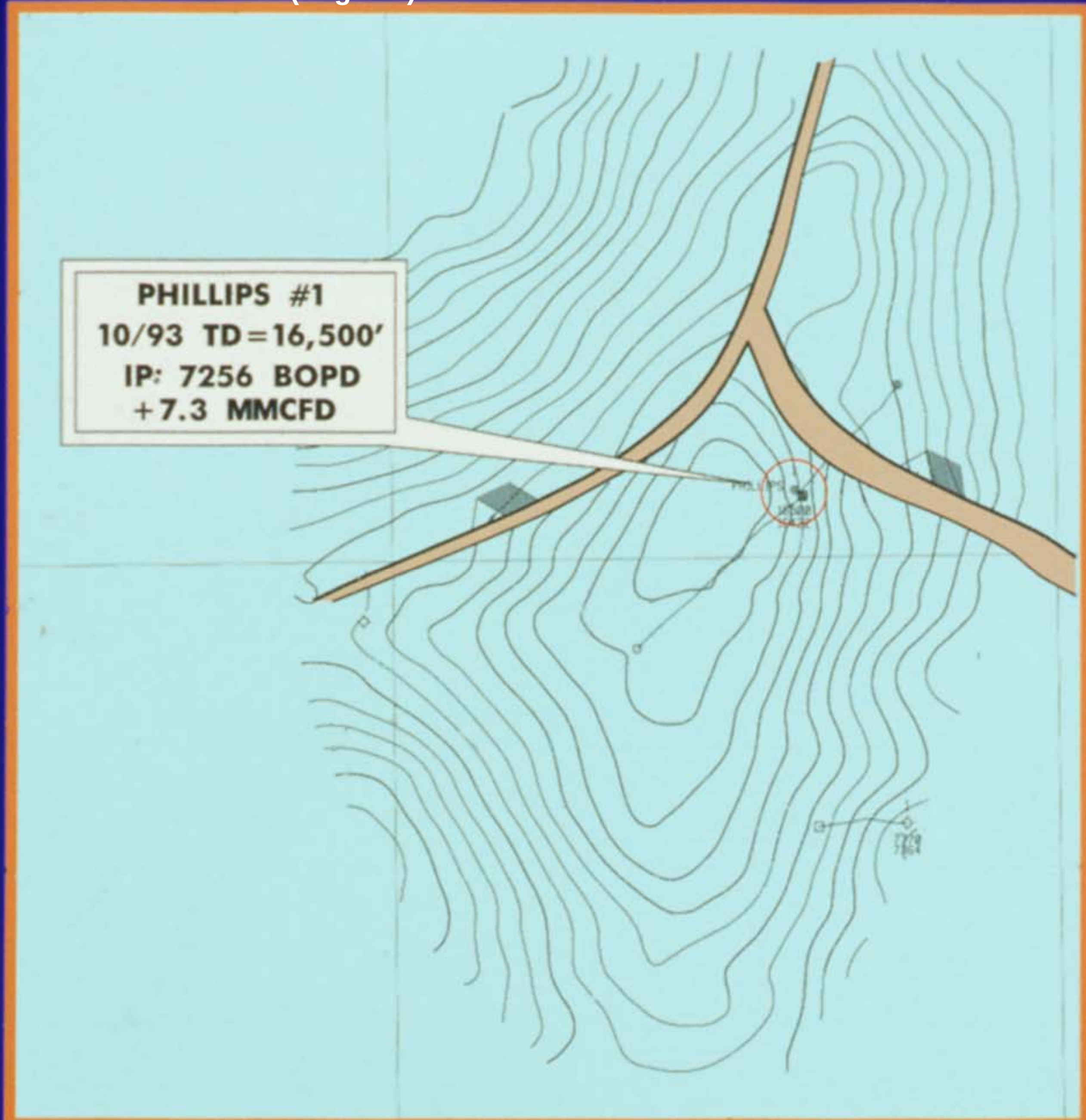

DEPTH STRUCTURE MAP

PRE-STACK DEPTH MIGRATED 3-D SEISMIC

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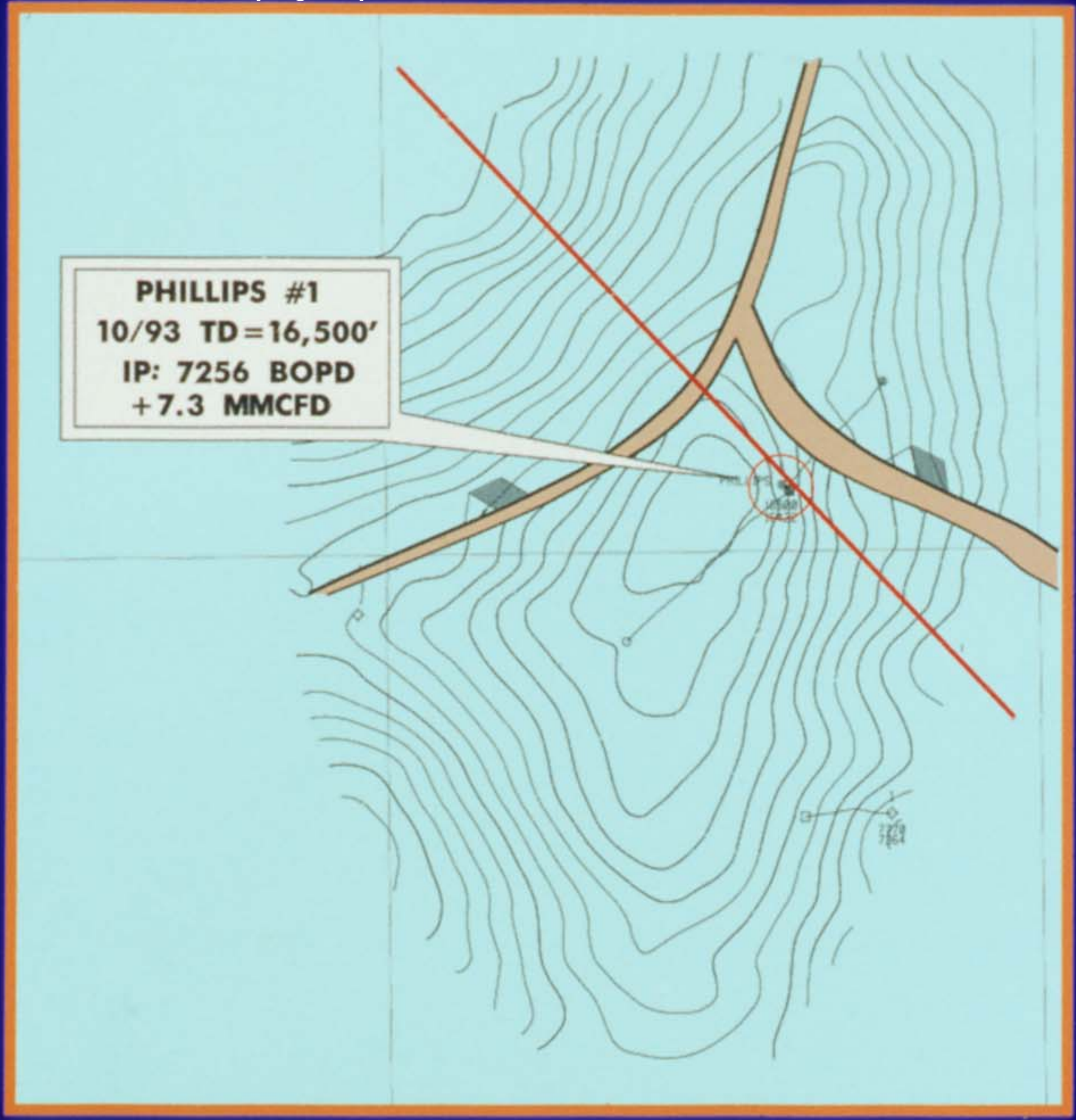

DEPTH STRUCTURE MAP

PRE-STACK DEPTH MIGRATED 3-D SEISMIC

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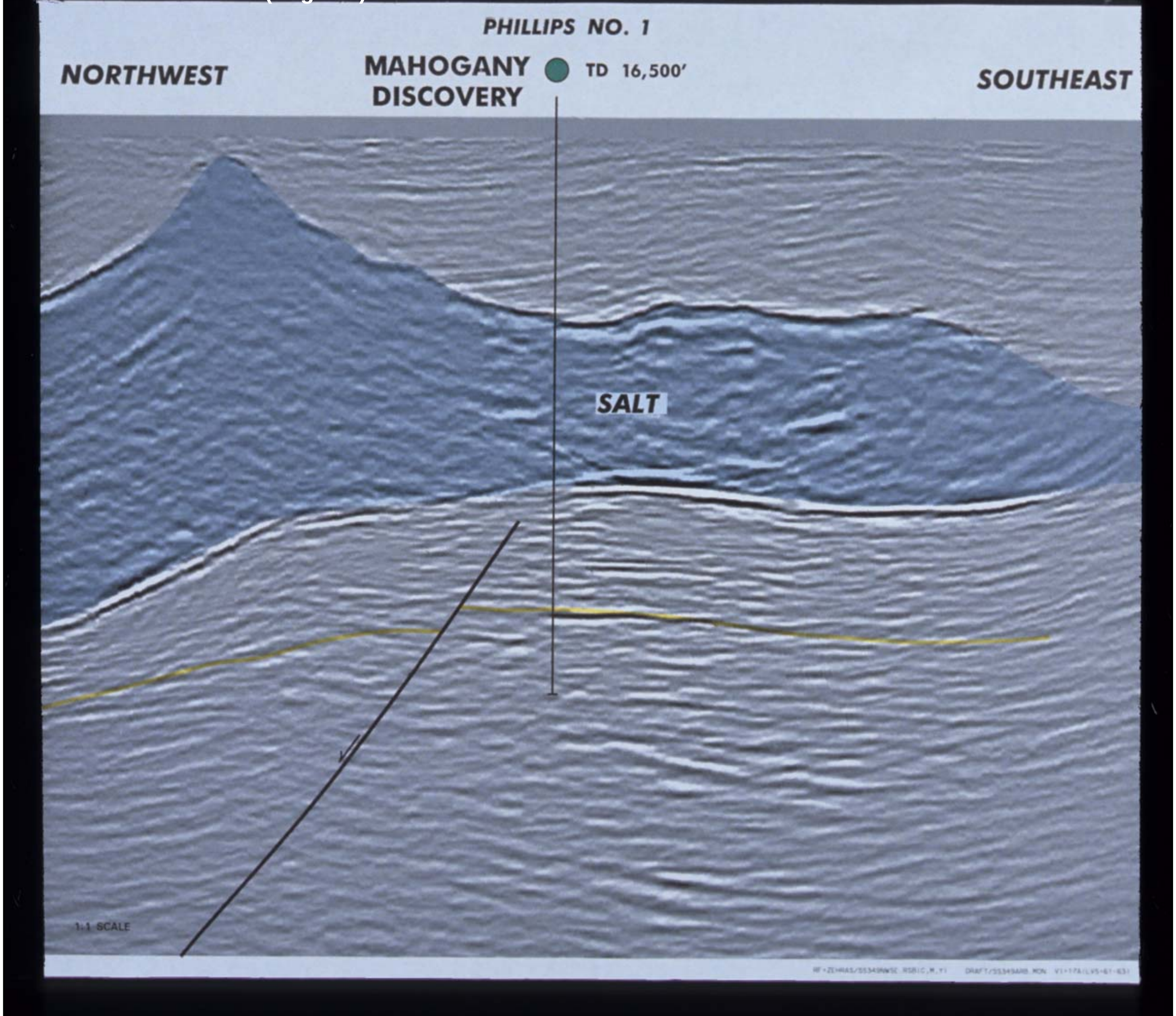
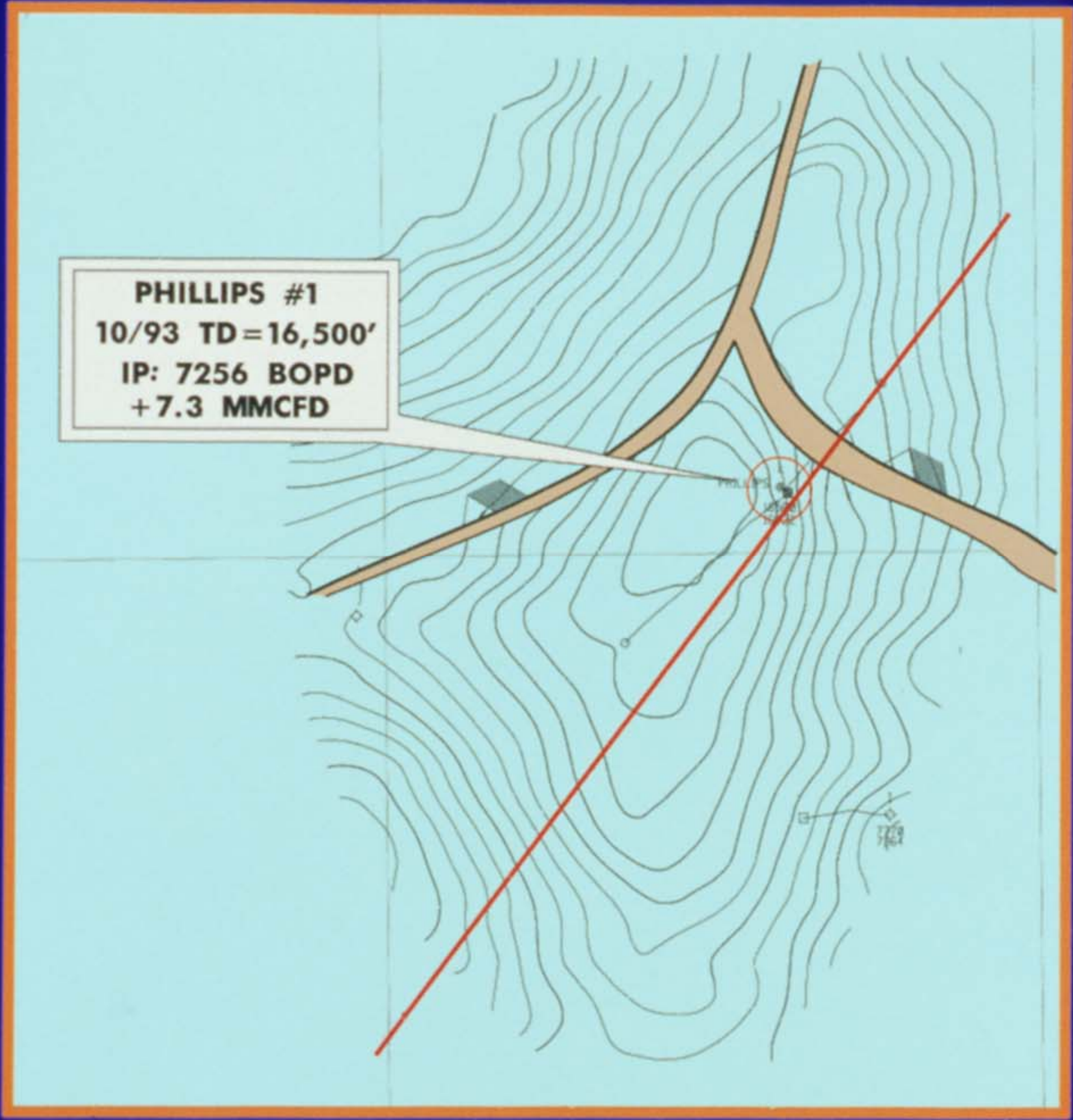
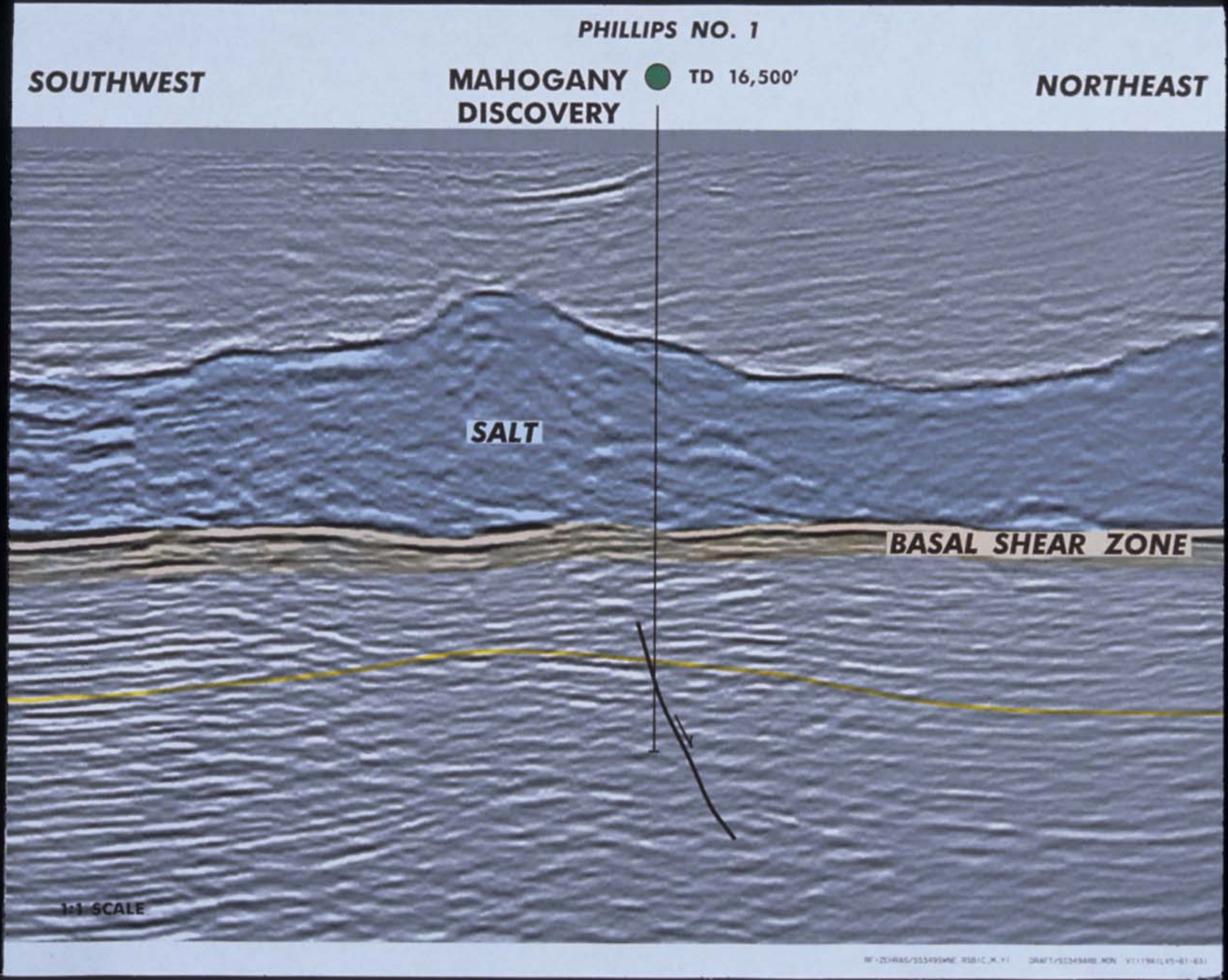




DEPTH STRUCTURE MAP

PRE-STACK DEPTH MIGRATED 3-D SEISMIC


PHILLIPS NO. 1
SOUTHWEST
MAHOGANY
DISCOVERY
TD 16,500'
NORTHEAST
SALT
BASAL SHEAR ZONE
1:1 SCALE

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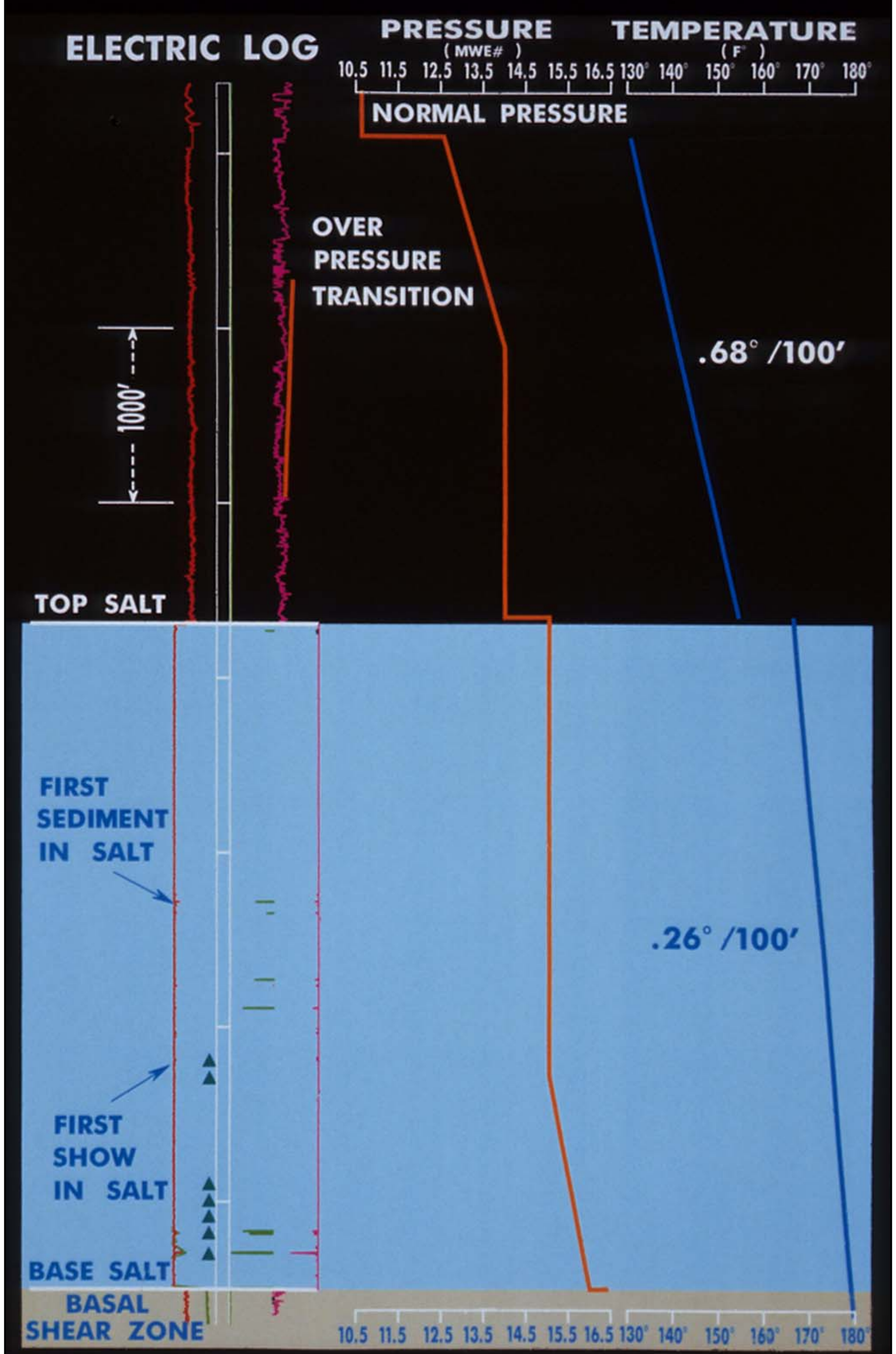

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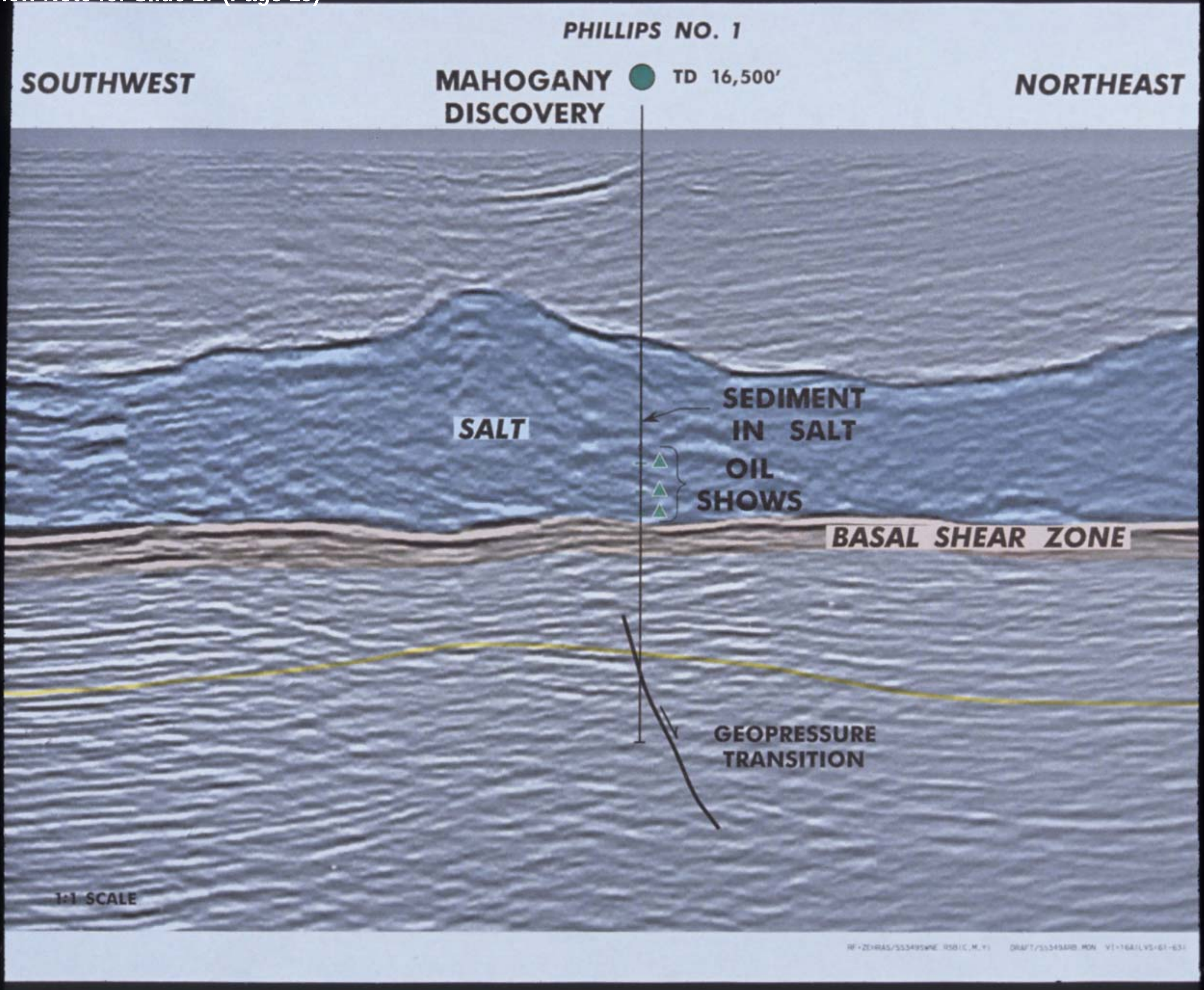

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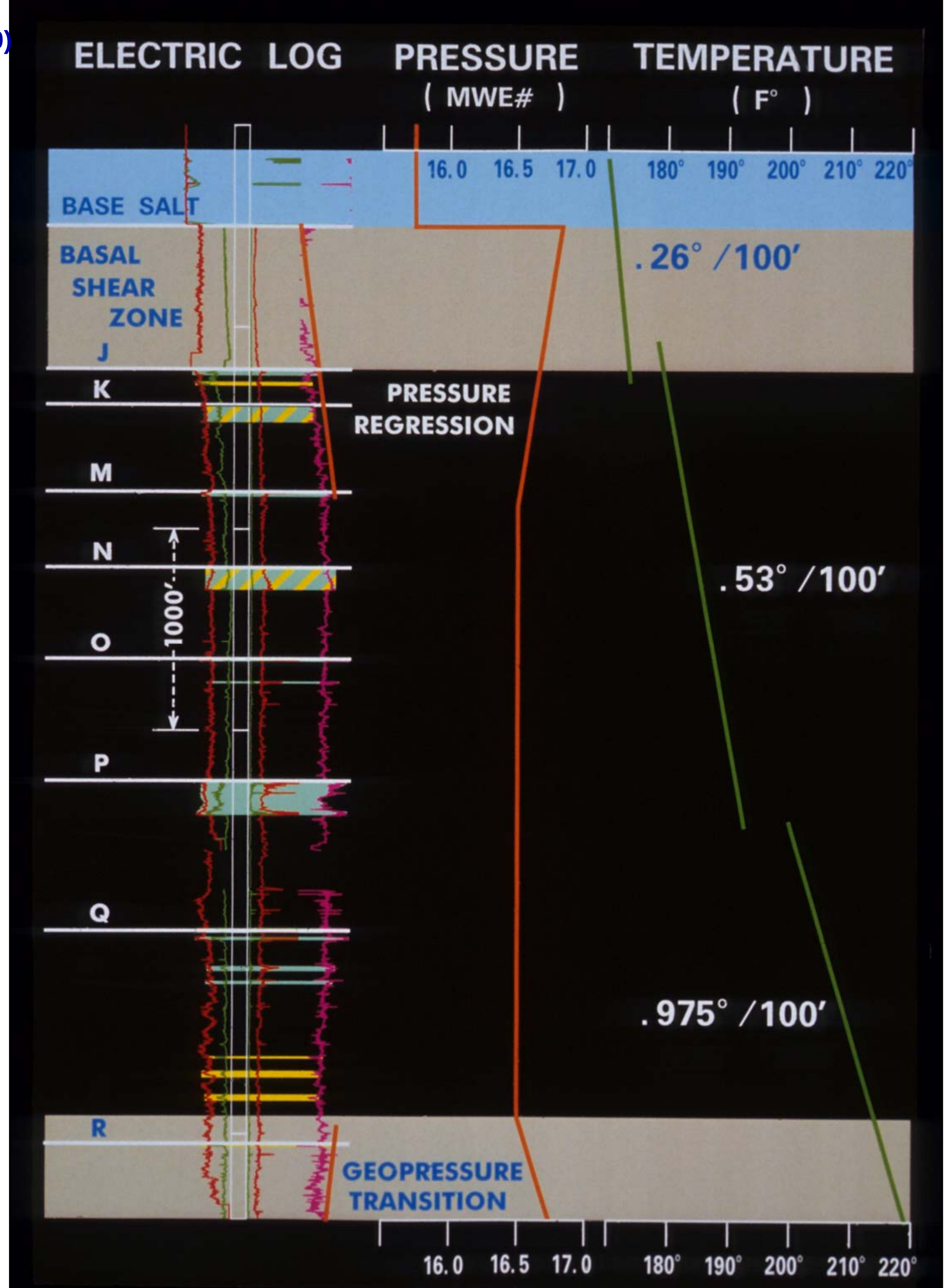

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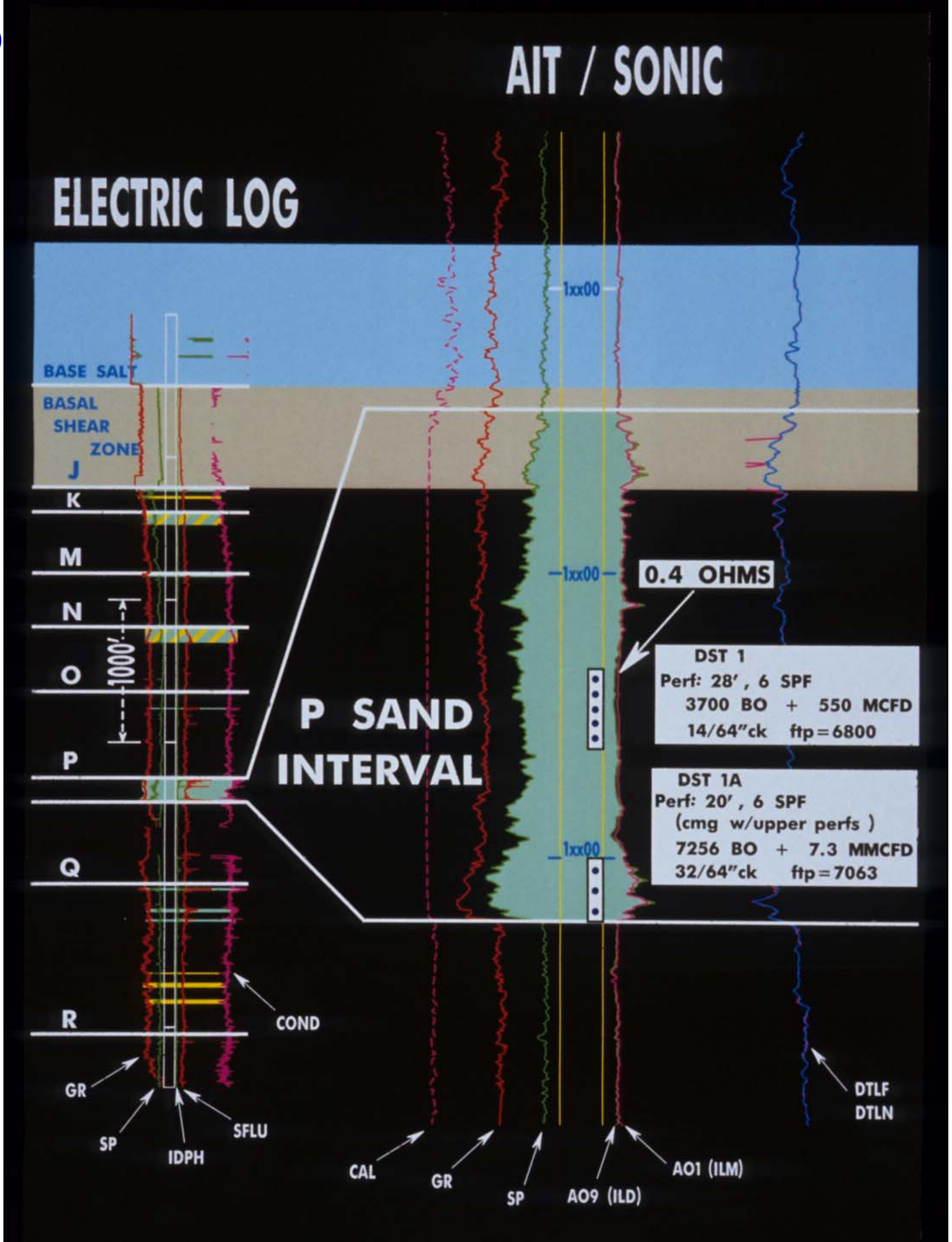

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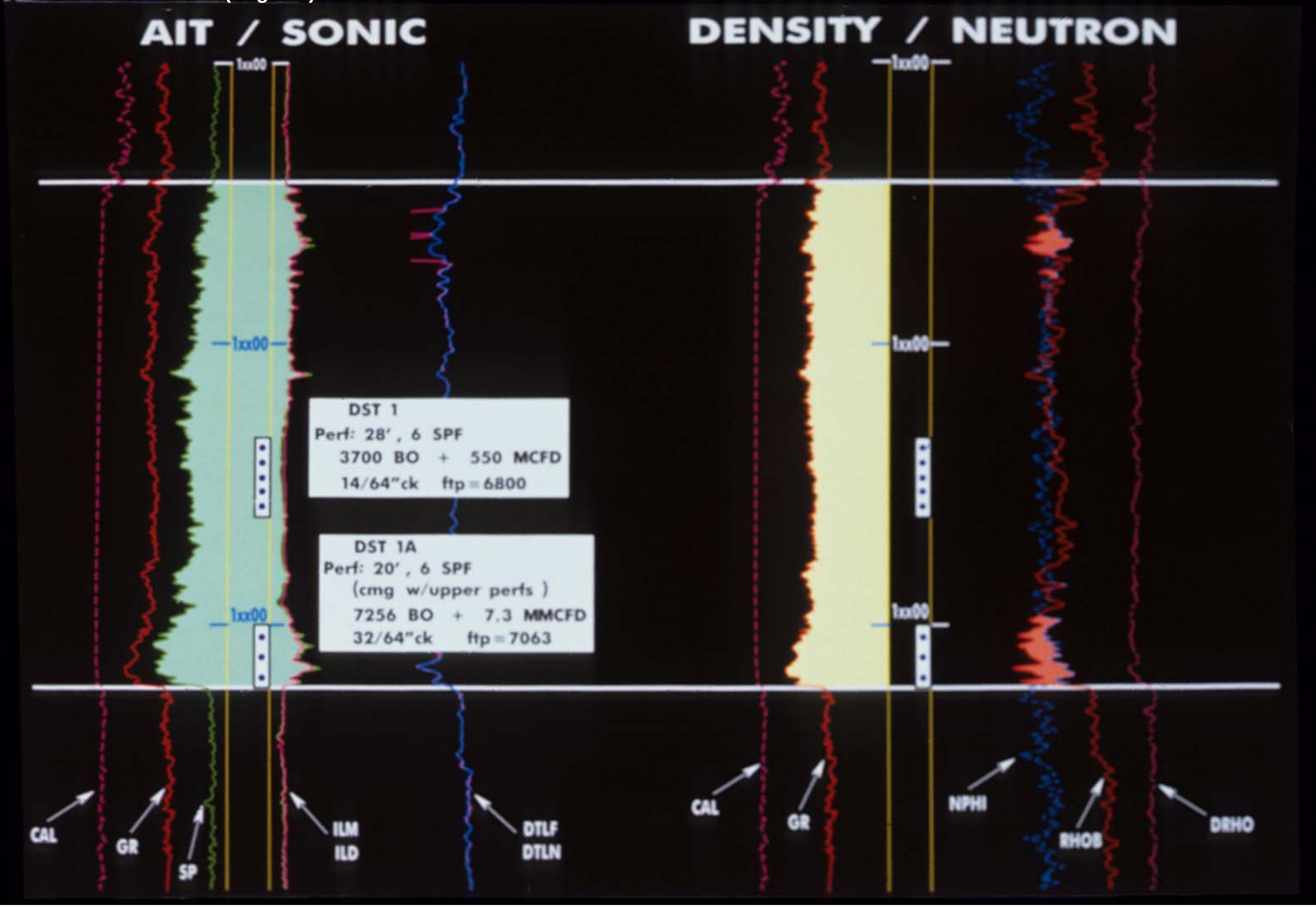

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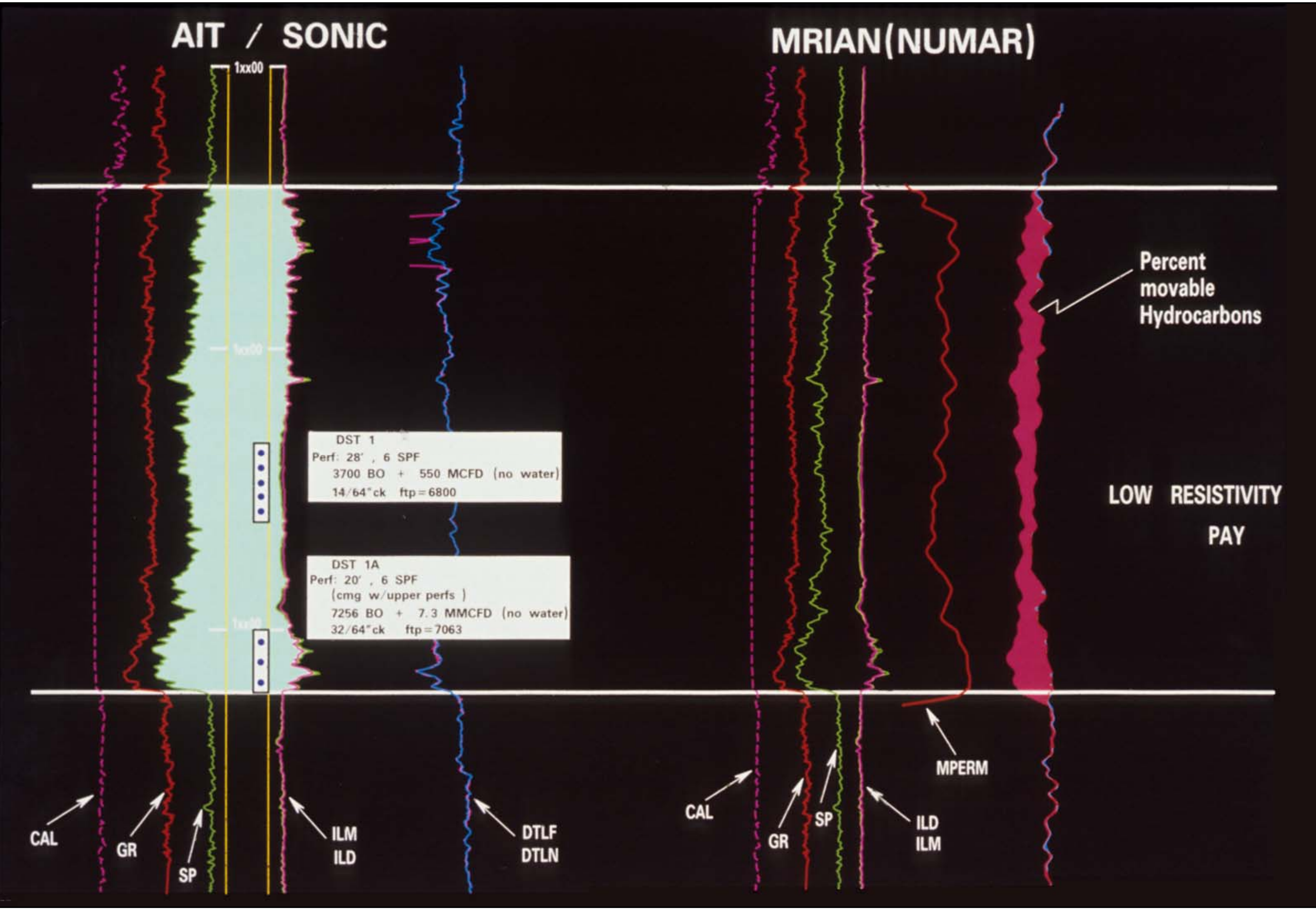

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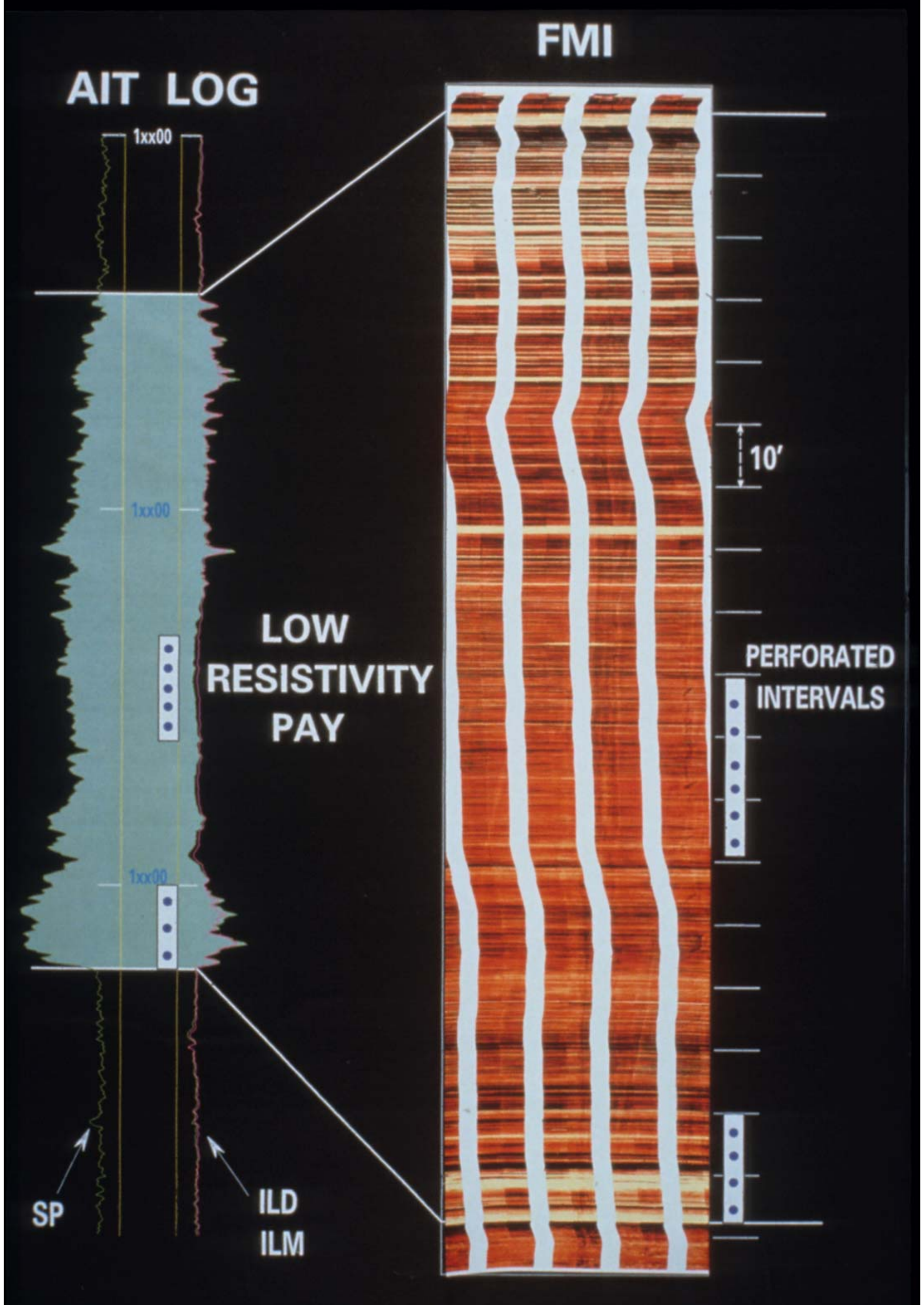

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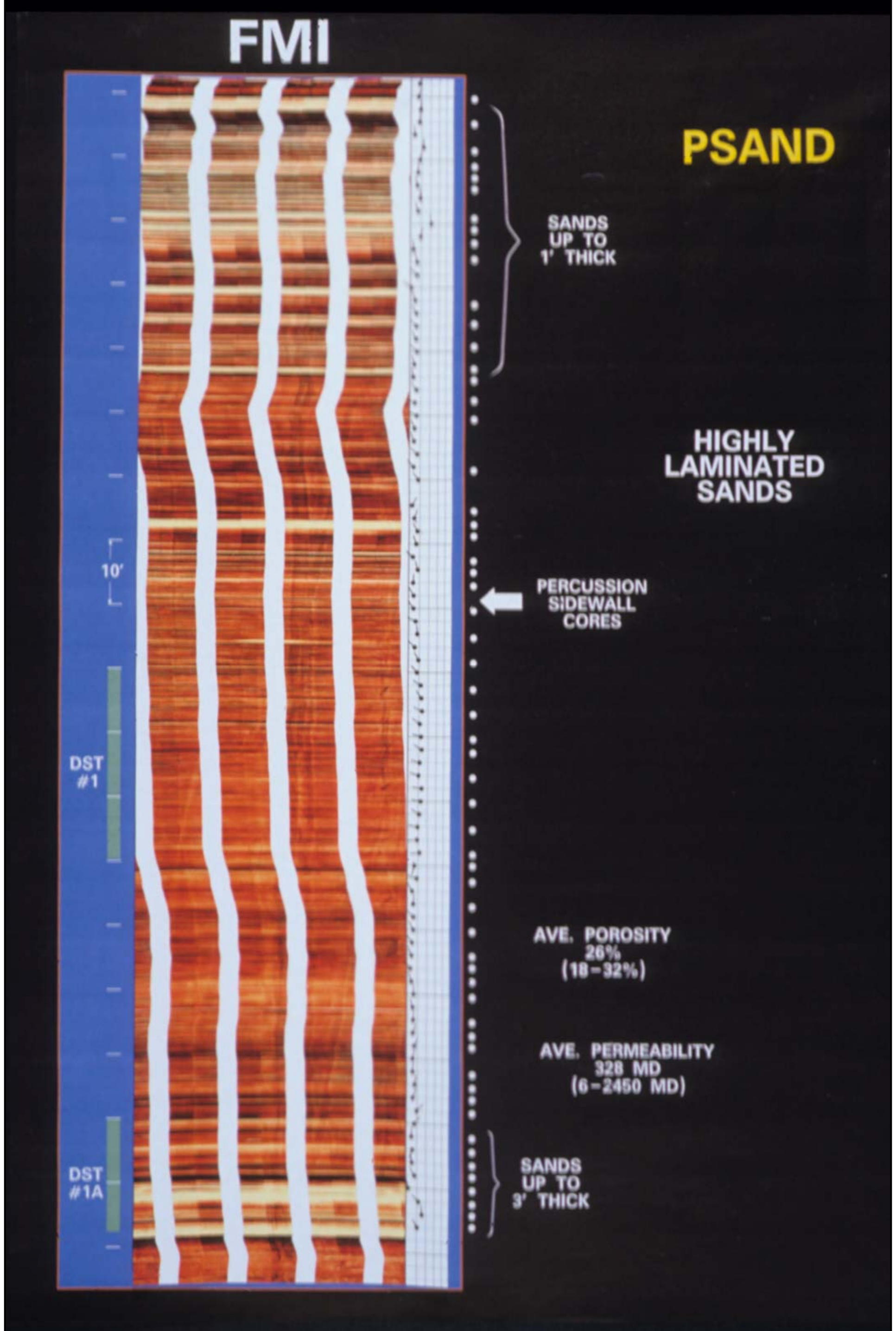

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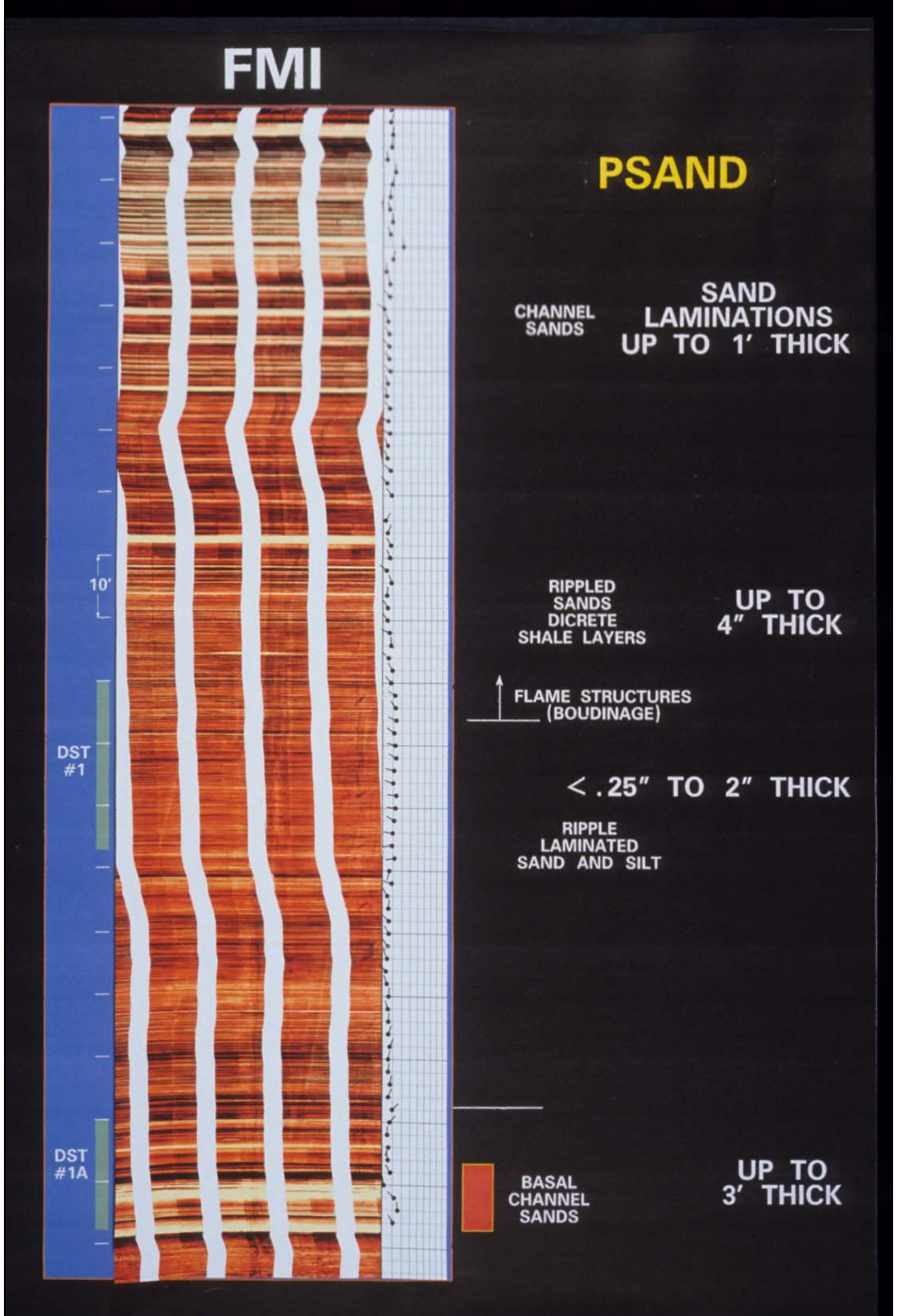

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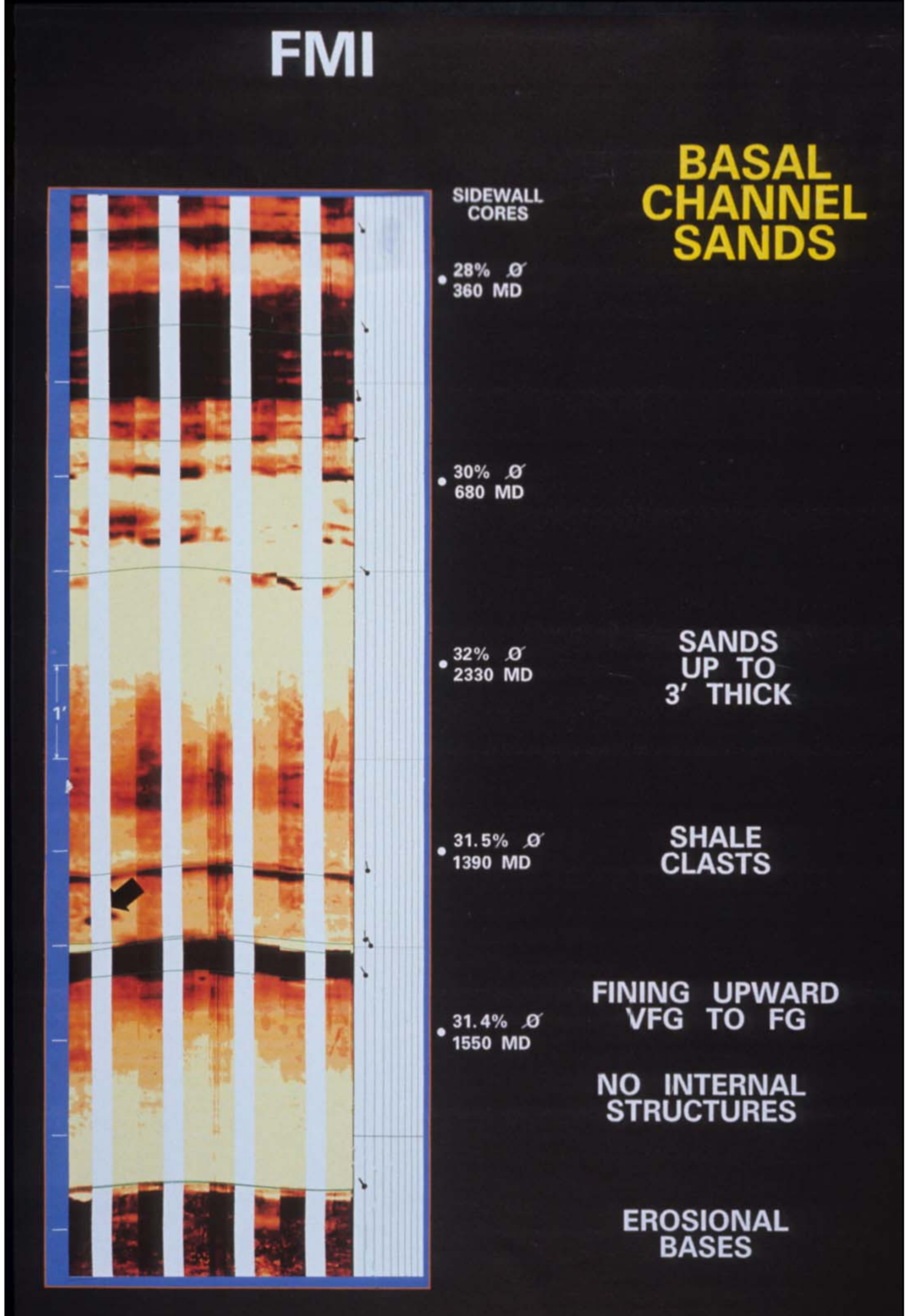

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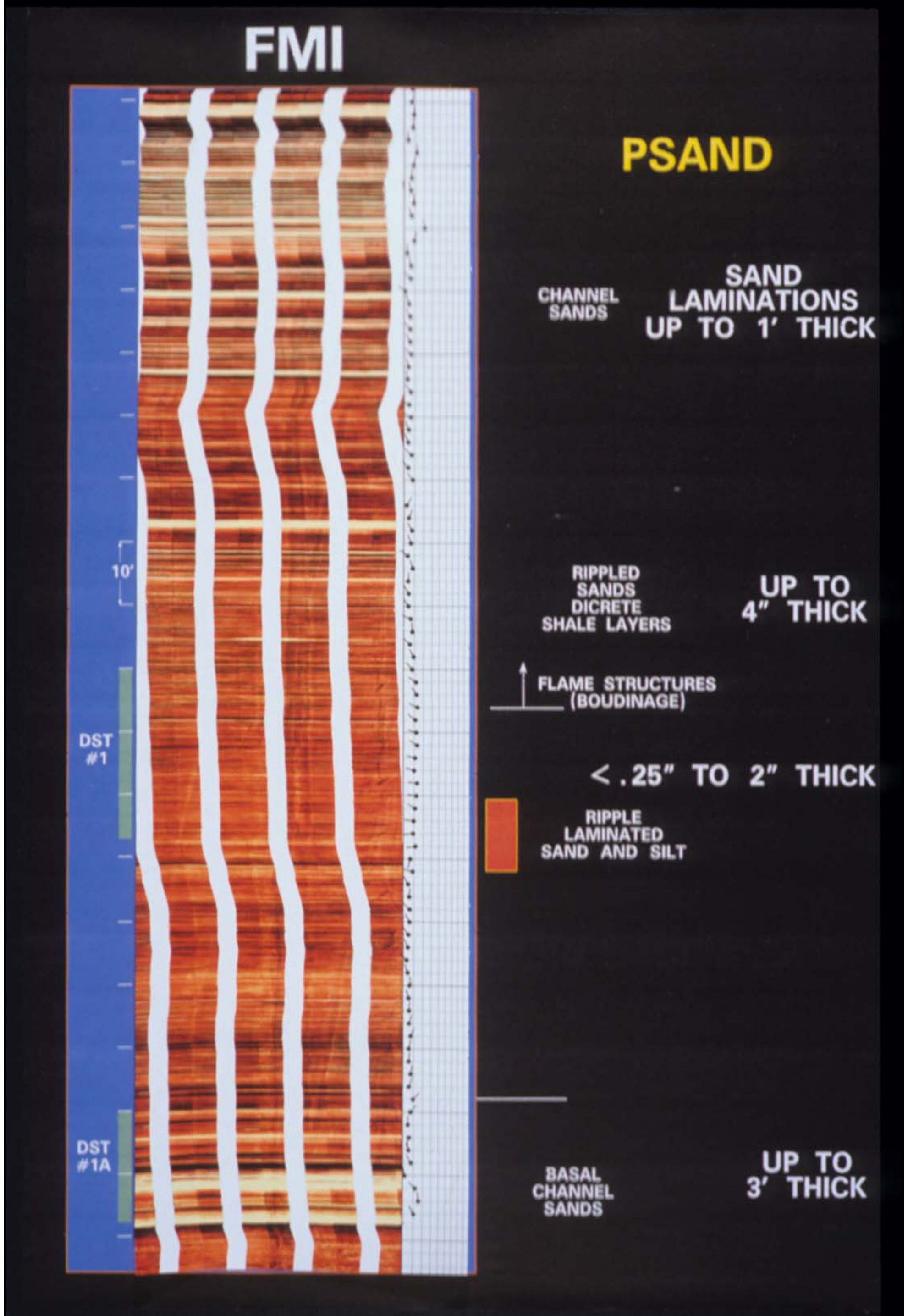

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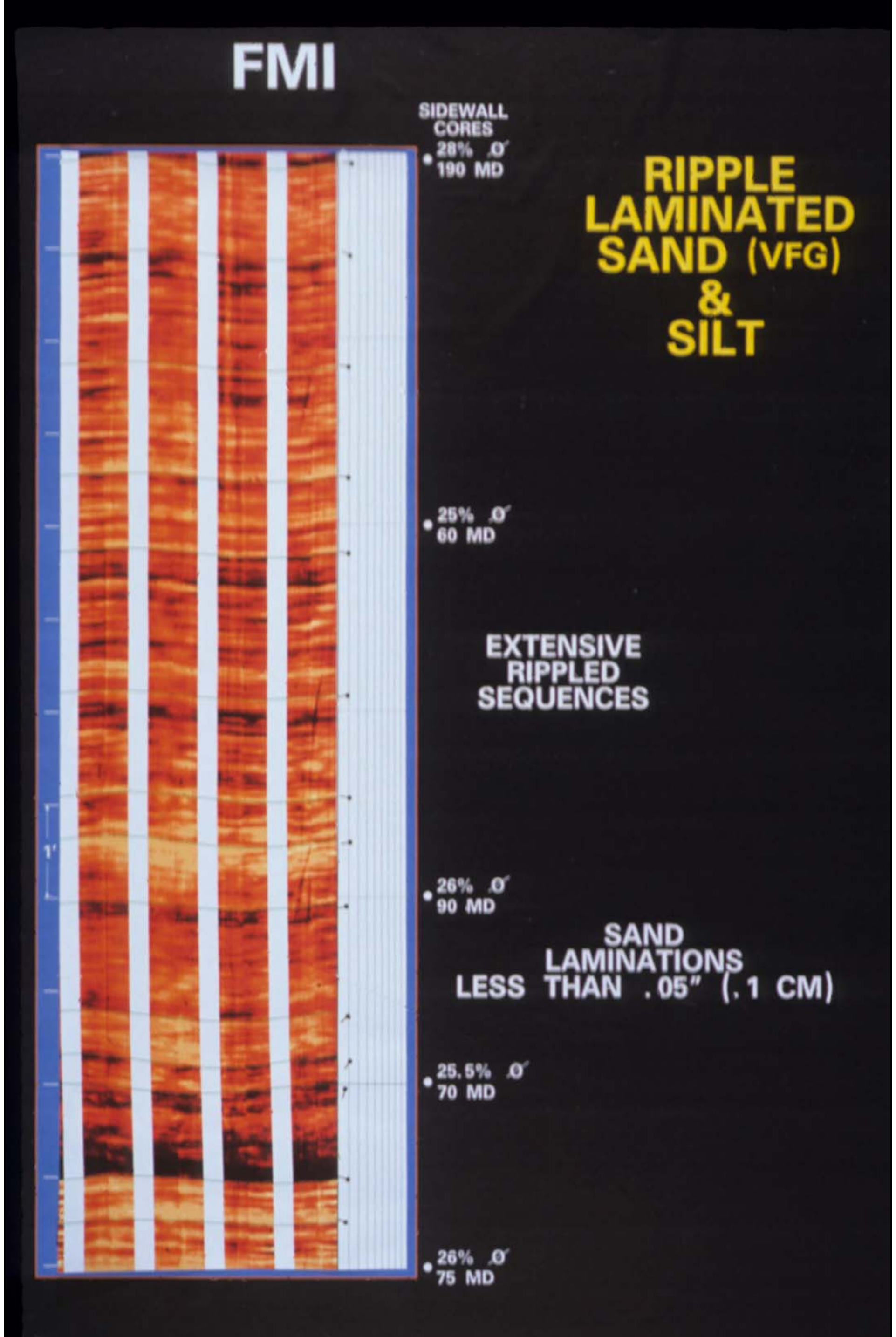

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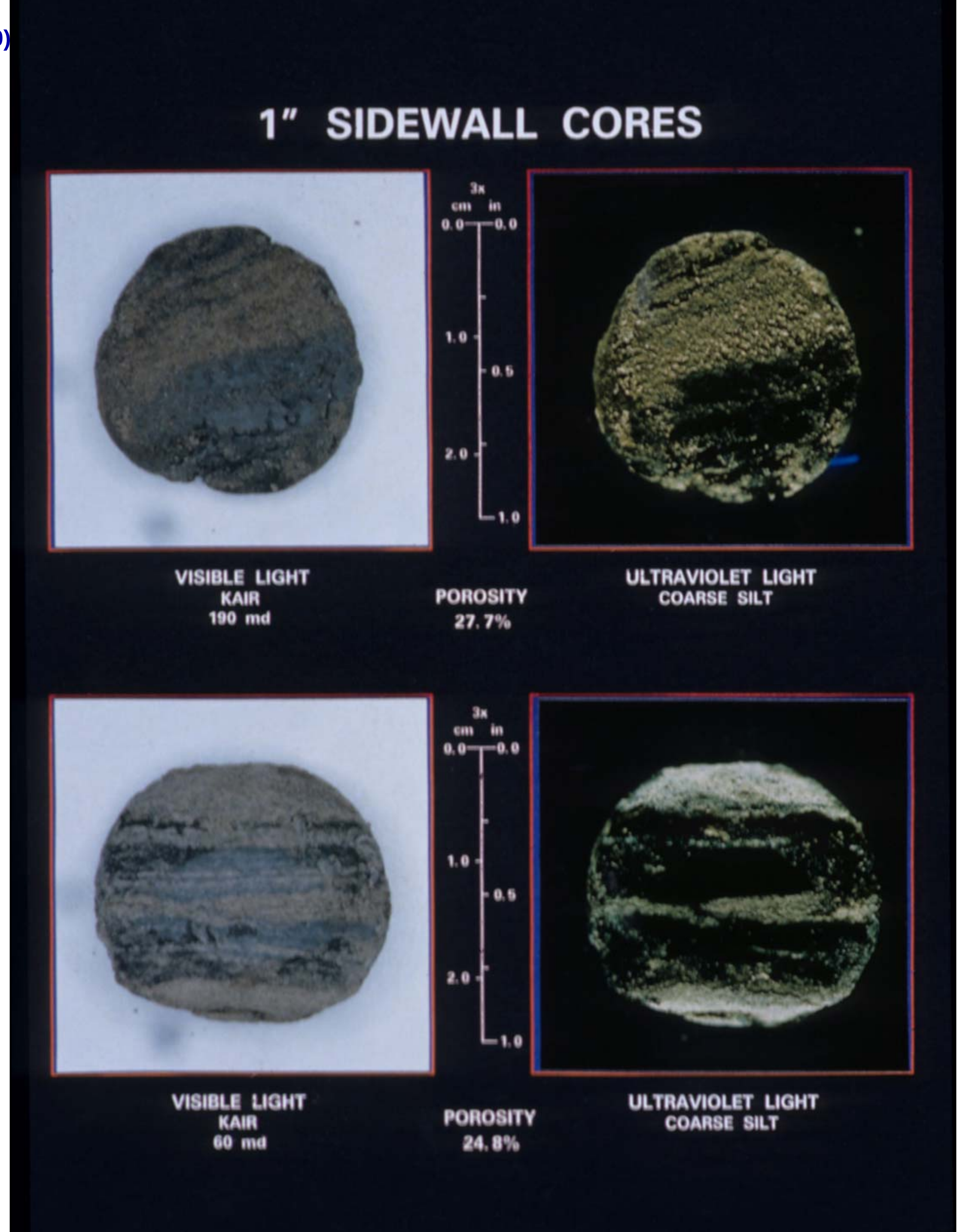

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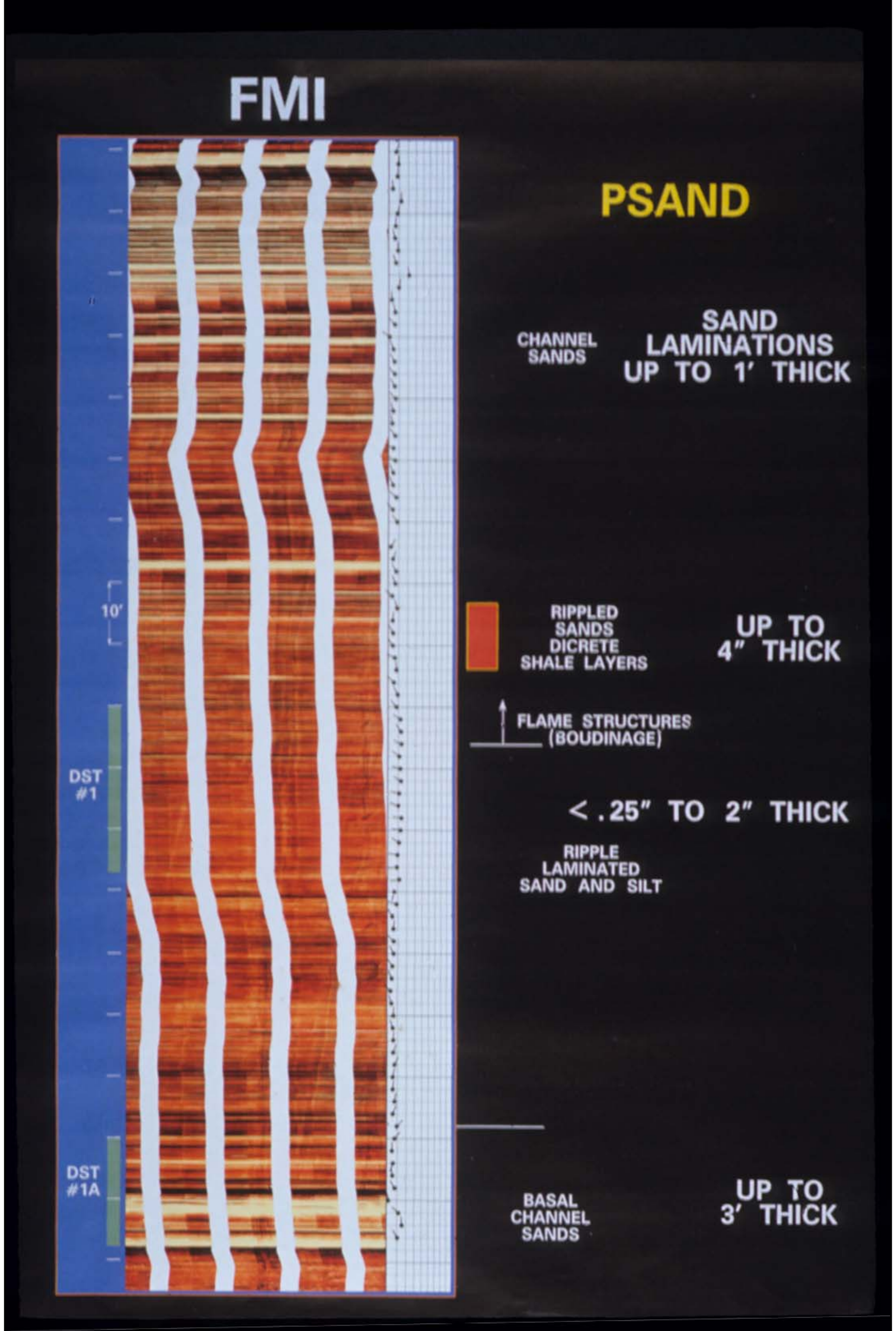

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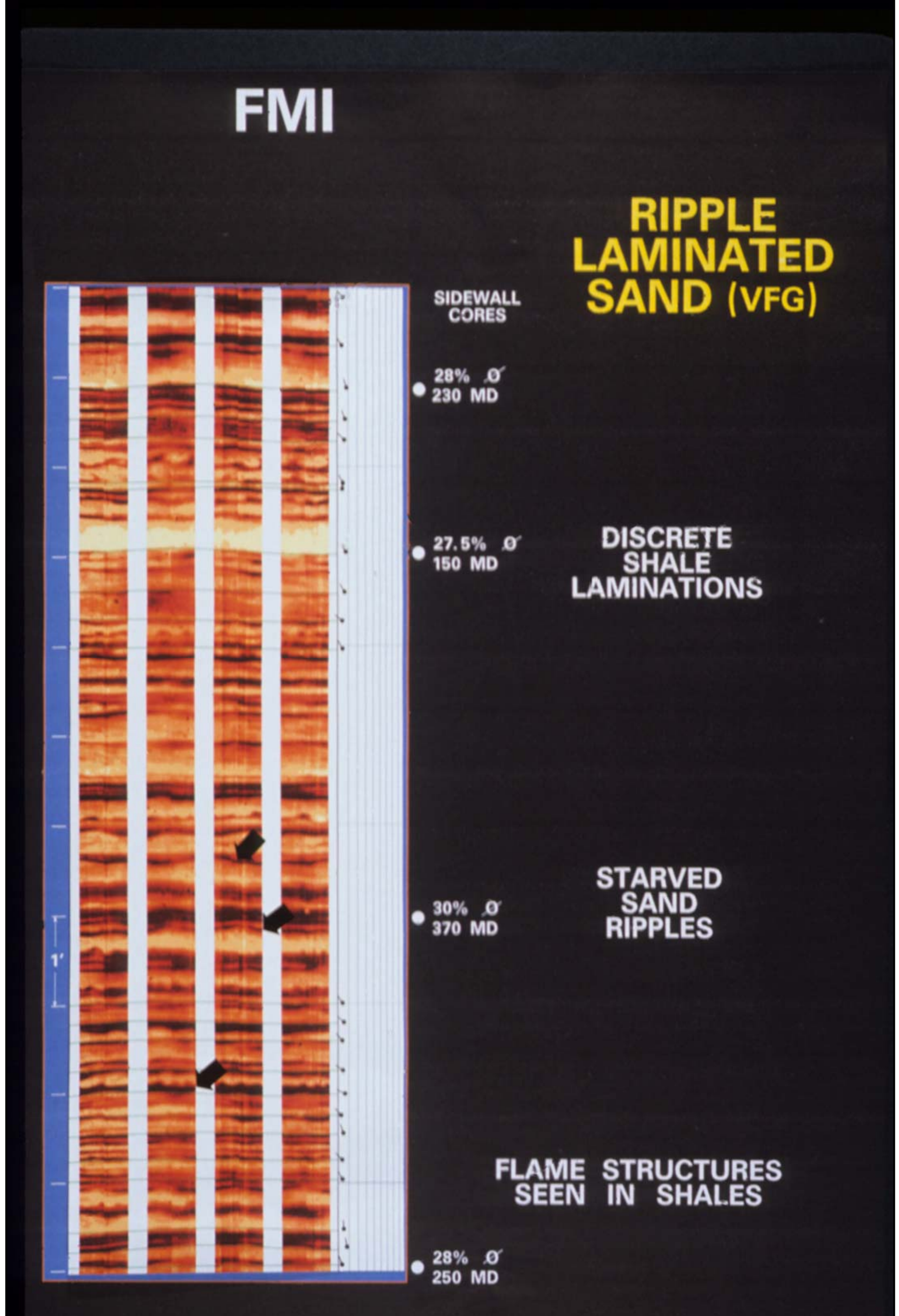

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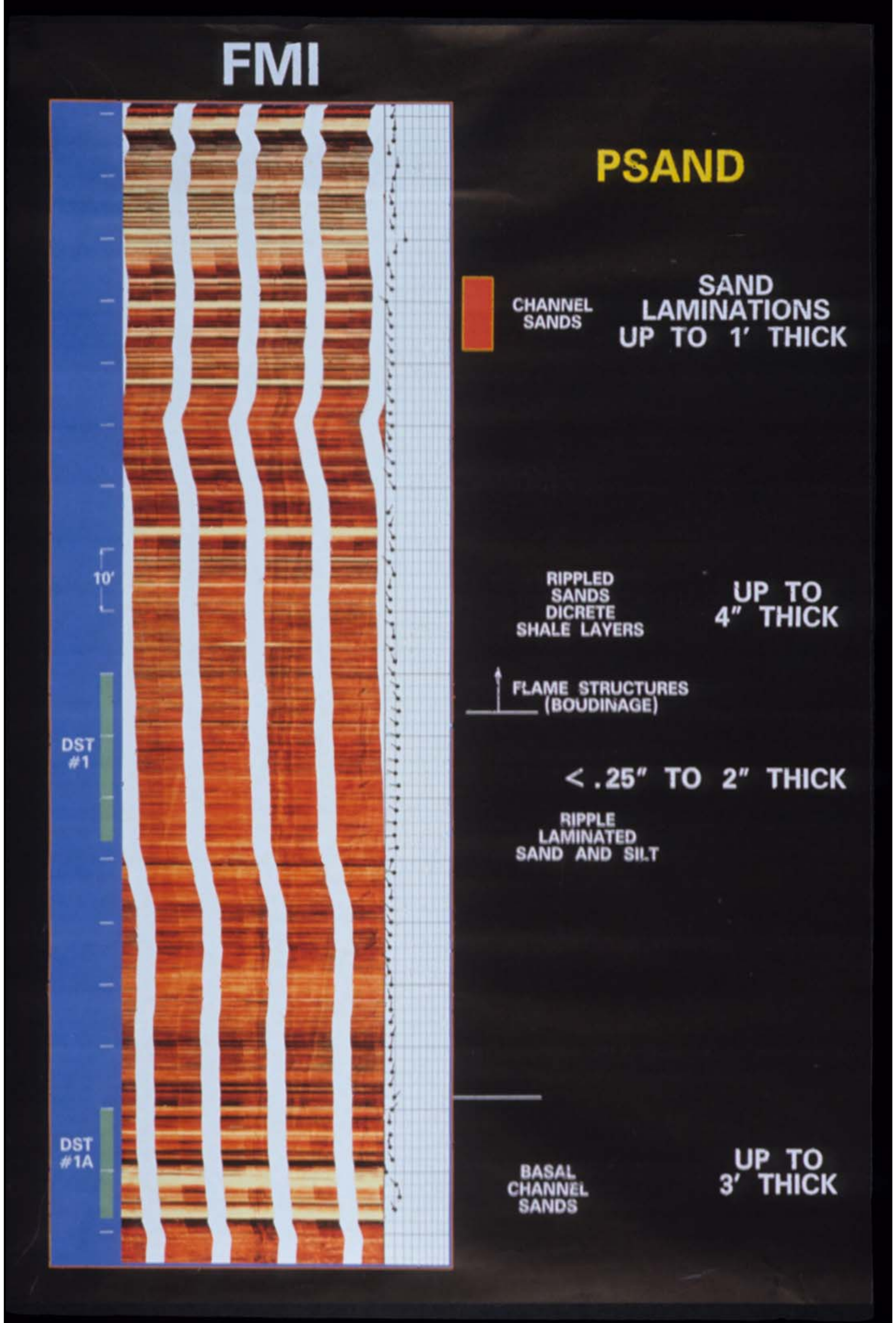

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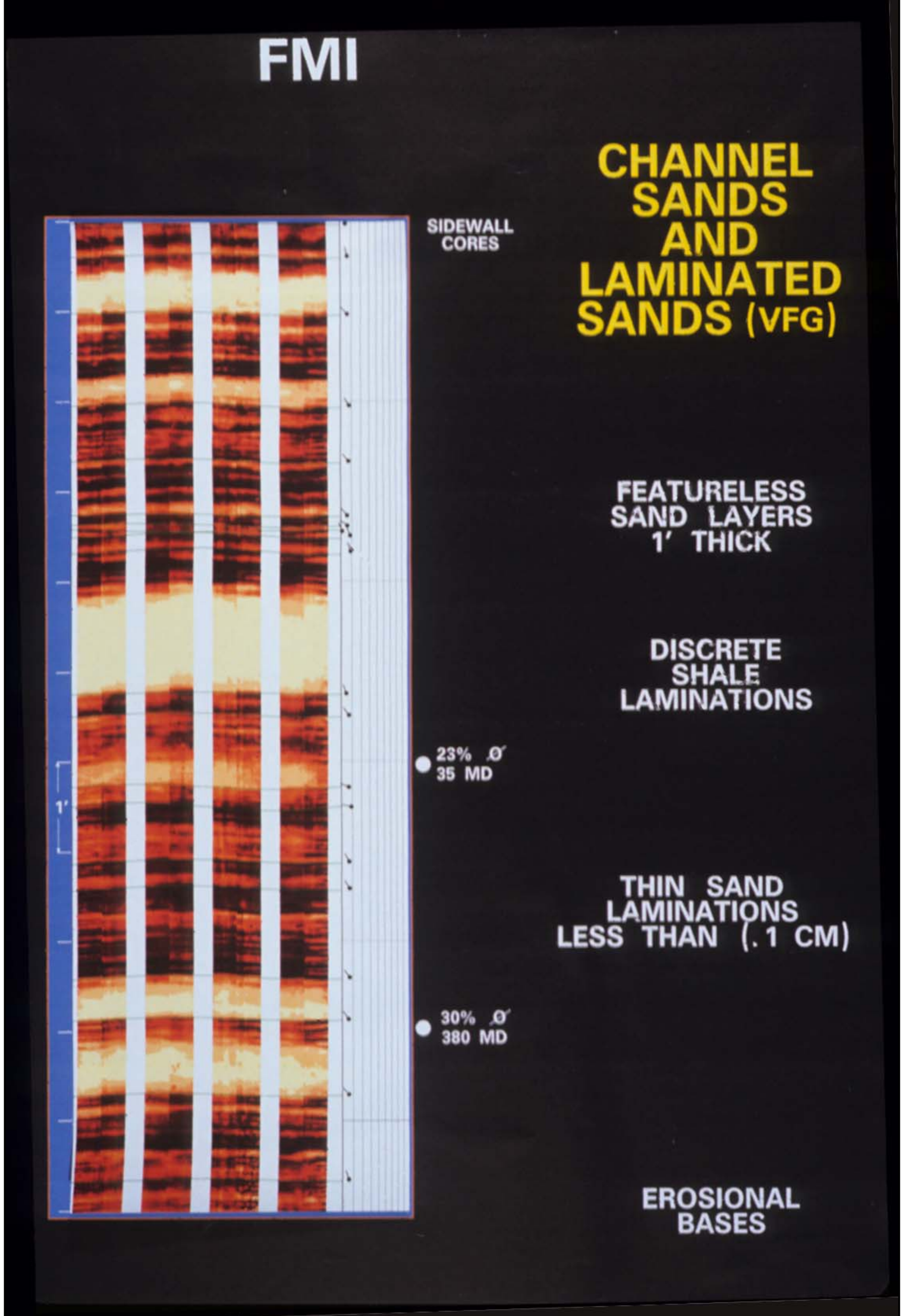

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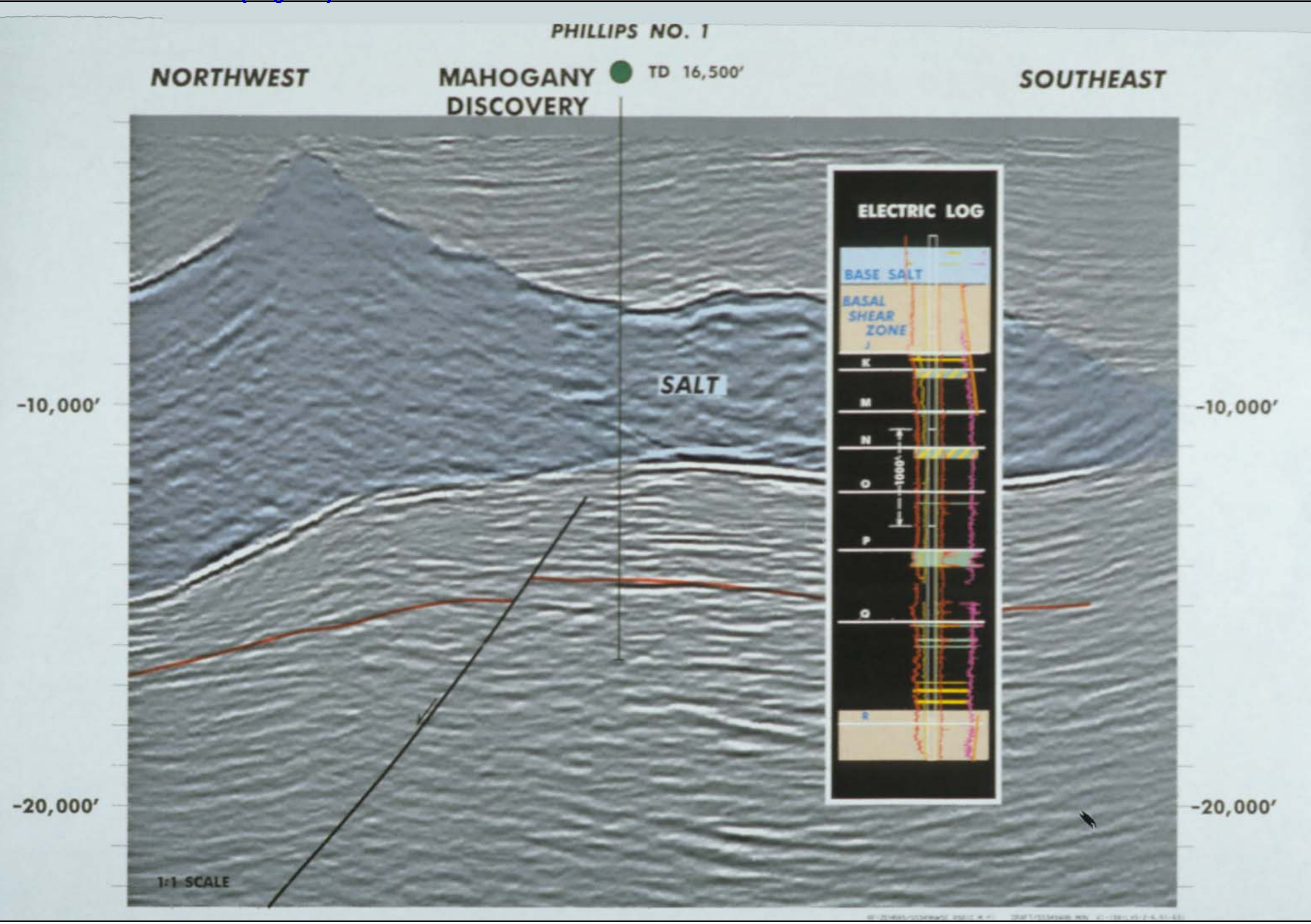

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CONCLUSIONS

- MAHOGANY IS THE 1st SUBSALT DISCOVERY ON THE SHELF IN THE GULF OF MEXICO
  - A FAULTED ANTICLINE OVERLAIN BY ALLOCHTHONOUS SALT
  - DEEPWATER SAND FAIRWAYS EXTEND UNDER THE SALT SHEET

- SUBSALT RESERVOIRS HAVE TREMENDOUS DELIVERABILITY
  - HIGH PRESSURE OIL SANDS (0.86PSI/FT OR #16.6MWE)
  - HIGH K AND Ø - (UP TO 2.5 DARCIES AND 33% Ø)
  - EXCEPTIONAL FLOW RATES

- LOW RESISTIVITY PAYS ARE NOT DEFINED BY STANDARD LOGS
  - RESOLVED BY WIRELINE IMAGING (FMI)
    - > LAMINATIONS DOWN TO 0.25" CAN BE RESOLVED
    - > CORES HAVE LAMINATIONS DOWN TO MICROSCOPIC SCALE
  - MRIAN LOGS CAN RESOLVE LOW RESISTIVITY PAY

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ACKNOWLEDGEMENTS

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MARK LEACH, JERRY DRAKE, FRANK SNYDER,
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ANADARKO PETROLEUM CORP.

AMOCO PRODUCTION CO.

TGS - CALIBRE Geophysical Company

GECO - PRAKLA

Notes Accompanying Slides

Slide 1 (Page 3)
Although the subsalt play in the Gulf has been active since the early 1980s, it was the Mahogany discovery in 1993 that sparked activity in the play to new heights. We discuss some of the important geological points of the prospect first from a regional and then from a detailed perspective.
Drilled by Phillips as operator and partners Anadarko and Amoco. This is the first subsalt discovery on the shelf in the Gulf of Mexico.
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Slide 2 (Page 4)
To date, 27 wells have been drilled through the allochthonous salt since 1984 (red dots). The first discovery was in Mississippi Canyon 211 by Exxon in 1990. This well was in water over 4300 ft deep - on the slope. The Mahogany well also discovered hydrocarbons below salt, but the water depth is significantly shallower (372 ft) - on the shelf. In 1994 Phillips and Anadarko also announced the Teak subsalt oil discovery in 290 ft of water. Currently three significant subsalt wells are operating, two exploration and one delineation.
Return to Slide 2 (Page 4)

Slide 3 (Page 5)
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Slide 4 (Page 6)
Mahogany is generally on trend with Bullwinkle, Boxer, and Green Canyon 18 fields. These oil fields produce from Pleistocene and Pliocene slope sands - referred to as the flex trend because of the shelf/slope flexure.
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Slide 5 (Page 7)
Although some wells on top of the sheets had oil and gas shows, these are no significant accumulations above salt. To date, the Mahogany salt sheet has four penetrations, more than any salt sheet in the Gulf. The Ewing Bank thrust is an interesting structural feature related to the salt sheets and will be used in the following slides to orient for you the structure. The Ewing Bank thrust runs the leading edge of the eastern salt sheet. Seismic line A-A’ is a north-south 2-D line that shows the thrust may become listric below salt.
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Slide 6 (Page 8)
The Ewing Bank thrust runs the leading edge of the eastern salt sheet. Seismic line A-A' is a north-south 2-D line that shows the thrust may become listric below salt. The area has multiple salt sheets at several depths, implying different emplacement and burial histories. Please note the resolution of large-scale structural features below salt, such as large Pliocene/Miocene basins, deep rooted salt highs, and bounding fault systems. Clearly on this section, the early drilling was mainly for above salt structures and amplitude anomalies, whereas the deeper features were untested. Also important to the subsalt play is recognition of differences between thin-skinned tectonics above salt and deeper 'thick-skinned' tectonics. The structures above and below salt are mostly not linked, but some genetic ties can sometimes be inferred. For example, the imbricate nature of the Ewing Bank thrust system correlates with subsalt highs and lows.
The Ewing Bank is a drowned Pleistocene reef that was moved upward into the photic zone by secondary diapirism on the salt sheets.
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Slide 7 (Page 9)
Deep salt features under allochthonous salt on 2-D data can be mapped and tied with regional mapping in the area. Line B-B' runs from a deep basin in the SW to a deep basin in the NW. The Ewing Bank thrust terminates along this edge of the salt sheet system and emphasizes the separation of the structures above and below salt. Again, note the shallow well penetrations that test above salt structures only.
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Slide 8 (Page 10)
Line B-B' runs from a deep basin in the SW to a deep basin in the NW. The Ewing Bank thrust terminates along this edge of the salt sheet system and emphasizes the separation of the structures above and below salt. Again, note the shallow well penetrations that test above salt structures only.
Determination of sedimentary patterns in the deepwater slope environment is a function of paleobathymetric geometry. The deep salt highs will have acted as buttresses and deflected sand deposition as turbidite currents flowed down-slope. Slope sands are therefore sensitive to bathymetry and will concentrate into sand fairways. These two fairways are clear; it is this salt high which is critical to the Mahogany Prospect. The prospect is west of a deep salt high which deflected sand to form a fairway across the acreage.
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Slide 9 (Page 11)
This map shows the probable distribution of sedimentary fairways below the Mahogany salt sheet. The deep salt high (below the salt sheet) funnels sands across the anticline. After sediment deposition, the salt became mobile and flowed down from the north approximately 8-12 miles from the deep source root that fed it, to blanket the structure with allochthonous salt.
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Slide 10 (Page 12)
Line C-C' shows the important strike relationships of fairways and deep salt highs. Green Canyon 18 field pay sands are in a younger Pleistocene fairway above a buried salt sheet. However, two older Plio-Miocene fairways flank either side of this younger fairway. The

western fairway is the key to sand deposition at Mahogany, and can be traced updip under the salt sheet.
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Slide 11 (Page 13)
The regional geologic work was integrated with the localized 3-D seismic depth interpretation seen here. Mahogany is basically a faulted anticline with 3-way dip closure. The discovery well was drilled four miles from the edge of the salt sheet. The detailed structure map shows only a generalized structure and interpretation of new data is ongoing. Also, the distribution of reservoir sand varies across the structure.

We now move on to a more detailed picture of the Mahogany Discovery.
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Slide 12 (Page 14)
Structure is anticline bounded on the north by northwest and northeast dipping faults. Line of NW-SE seismic section in Slide 13 (Page 15).
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Slide 13 (Page 15)
In the dip direction, the base of the salt dives to the northwest (towards the original source of the allochthonous salt). The northwest-dipping fault that cuts the anticline is clearly imaged on this data. The top and base of salt are also imaged as well as the secondary diapir formed on this part of the salt sheet. This seismic line and the following line are from a Phillips pre-stack 3-D depth migration and have no vertical exaggeration.
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Slide 14 (Page 16)
Structure is anticline bounded on the north by northwest and northeast dipping faults. Line of NE-SW seismic section in Slide 15 (Page 17).
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Slide 15 (Page 17)
The strike line shows the anticlinal closure to the southwest and the northeast. There are indications of other smaller faults which complicate the structure. The base of salt is more even and gently concave in the strike orientation..
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Slide 16 (Page 18)
The SS 349 #1 well drilled very little sand above salt. This slide has a electric log, the pore pressures as mud weight per gallon, and temperature. Pressures and temperatures were typical for above salt wells in the area. Sedimentary inclusions within the salt were first encountered halfway through salt which is over 3500 ft thick. The first oil show was 2/3 the way through the sheet. The temperature gradient in the salt was low due to the high thermal conductivity of salt. Rotary sidewall cores were cut in the salt and analyzed for viscosity and

strain to help determine salt mobility which can impact long-term casing design.
Although salt is an incompressible rock and should have no variations in pore pressure, the sedimentary inclusions within the salt made it necessary to increase mud weights to control gas. Mud weights were also increased in anticipation of the subsalt section.
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Slide 17 (Page 19)
SW-NE seismic line, with annotations about sedimentary inclusions within the salt, the underlying sediments, and pressure regime. SS 349 #1 drilled very little sand above salt. Pressures and temperatures were typical for above salt wells in the area. Sedimentary inclusions within the salt were first encountered halfway through salt which is over 3500 ft thick. The first oil show was 2/3 the way through the sheet. The temperature gradient in the salt was low due to the high thermal conductivity of salt.
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Slide 18 (Page 20)
The well came out into high-pressured gumbo shales below salt, referred to as basal shear zone. This zone, which is typically seen in subsalt wells, has pore pressures that may exceed #17ppg pressure gradients (0.88psi/ft). Pressure gradients regress with depth below the salt sheet back to more regional gradients (although still geopressured). Note the conductivity curve is increasing with decreasing pressure.
The shallowest oil sand at Mahogany is the ‘J’ sand in the pressure transition zone. There are multiple pay zones, but the primary target is the P sand. Water-bearing sands are found just below the J sand and starting in R sand interval. Pressure increases once more near the bottom of the well. Salt has a large temperature halo below and the gradients gradually increase downward from the base of salt.
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Slide 19 (Page 21)
The P sand target interval was flow tested in two stages. DST 1 perforated 28 ft and flowed 3700 BO and 550MCFD on a 14/64” choke at 6800 PSI flowing tubing pressure. Perforations from the base of the sand were then added and the commingled flow rate was 7256 BO and 7.3MMCFD on a 32/64” choke at 7063 PSI flowing tubing pressure. The selective test (DST 1) was across a very low resistivity interval where sensitivities are actually lower than the shales above and below the P sand (0.4 ohms). The lower DST interval has a more typical log response that indicates pay. The total perforated interval was 48 ft out of about 200 ft gross interval.
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In the P sand, as we know now, the low resistivity pay is caused by fine laminations of shale that alternate with thin sand and silt laminae of higher resistivity. Most logs do not have the vertical resolution to distinguish between the shale and pay sand; they average the responses. Wireline porosity logs (long spaced sonic, litho density, and neturon) also average the shale and sand and cannot resolve low-resistivity pay. The density-neutron logs, for example, have very little crossover in these zones. There IS crossover at the top and base where the resistivity is also higher, and this portion of the P sand calculates as pay.
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Slide 21 (Page 23)
Nuclear Magnetic Resonance data (seen here as a MRIAN log display) can distinguish between ineffective porosity and effective porosity. Processed with resistivity and porosity, the MRIAN log determines the percent of moveable hydrocarbons. This one of two open hole logs than can resolve the pay.
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Slide 22 (Page 24)
On the left is an Array Induction log that is run at 1-ft resolution. However, the tool that defines the nature and cause of the low resistivity pay is the Formation Micro Imager (FMI). This tool has a resolution down to 0.25" and gives a better "picture' of what causes low resistivity. The FMI reveals a highly laminated interval with discrete shales and sands. The sands are yellow and the silts are orange.
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Slide 23 (Page 25)
This is the FMI images of the P sand interval with the location of percussion sidewall cores (see Slide 28 [Page 30]) and dips. The scale is 10 ft. The average core porosity is 26% (ranging from 18-33%), and permeability is 32% millidarcies (ranging up to 2.5 darcies). The sands at the base are up to 3 ft thick; there is an extensive section of very finely laminated sands, with thicker sand beds at the top.
The P sand was deposited in deepwater, and the dip changes indicate multiple episodes of sedimentation. The sequence is probably composed of channels and levee deposits with a thick interval of rippled silt and sand.
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Slide 24 (Page 26)
FMI images of the P sand interval with the section from the lower part of the sand shown in Slide 25 (Page 27) highlighted in red.
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Slide 25 (Page 27)
This is a close-up of the section highlighted with red in Slide 24 (Page 26). The scale is 1 ft. The basal sands (which are relatively thick-bedded) have the coarsest grain size seen in the P sand (fine-grained sand). The sands have erosional bases, are either amorphous or fining upward, and contain some shale clasts. These are interpreted as channel sands deposited by density currents. This section was part of the perforated interval that flowed over 7000 BOPD and 7 MMCFD. Now, we move up the section.
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Slide 26 (Page 28)
FMI images of the P sand interval, with part of the section characterized by low resistivity highlighted in red; this is the interval represented by Slide 27 (Page 29).
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Slide 27 (Page 29)
The lowest resistivity section is an extensive sequence of ripple-laminated sand and silt--note that the image has blebby texture. Although porosities and permeabilities are lower than in the channel sands (60-90 md and 25% porosity), the selective DST on this zone flowed 3700 BOPD and 550 MCFD.
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Slide 28 (Page 30)
The two sidewall cores of this interval clearly show the scale of laminations. Position of cores is shown in Slide 23 (Page 25). The FMI can resolve laminations down to 0.25”, but the core indicates that even this tool may be too coarse. The scale of the laminations are microscopic. Silt has reasonable permeabilities and porosities.
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Slide 29 (Page 31)
FMI images of P sand; highlighted interval (in red), of section higher in the section characterized by low-resistivity, shows flame structures in shale layers. Detail shown in Slide 30 (Page 32).
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Slide 30 (Page 32)
Moving higher in the section, flame structures in shale layers become more apparent. This interval contains ripple-laminated sands and discrete shale laminations (some sands retain the original ripple geometry). This section is still very highly laminated and has variable dips.
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Slide 31 (Page 33)
FMI images of P sand interval, with highlighted section (in red) of channel and laminated sands that cap the sand. These are shown in more detail in Slide 32 (Page 34). Laminated beds are up to 1 ft thick, but unlike the basal channels this section has very finely laminated sands as well as thicker, featureless channel sands.
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Slide 32 (Page 34)
Channel and laminated sands cap the P sand, where laminated beds are up to 1 ft thick. Unlike the basal channels, however, this section has very finely laminated sands as well as thicker, featureless channel sands. This is a normal resistively pay interval.
Overall, the P sand has a fining-upward textural sequence, with a coarse-grained, more thick-bedded layer at the base, overlain by extensive rippled and highly laminated sands. With more core and log data, the areal geometry of the sands can be incorporated into an applicable deepwater depositional model.
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Slide 33 (Page 35)
NW-SE seismic line with position of discovery well and its log, which together provide a visual summary of the play.
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Slide 34 (Page 36)
In summary, the major conclusions about the Mahogany Subsalt Discovery are:

- It is the first subsalt discovery on the shelf in the Gulf of Mexico. It is a faulted anticline overlain by allochthonous salt. deepwater sand fairways were deposited prior to salt movement, and they extend under the salt sheets.
- Subsalt reservoirs have tremendous deliverability. They are high-pressure oil sands, have high K and phi (up to 2.5 darcies and 33% porosity), and have exceptional flow rates.
- Mahogany is also a case study for low-resistivity pays. Some of the pay sands encountered at Mahogany are not defined by standard wireline log suites. The pay can be resolved by Magnetic Resonance logs and imaging tools, such as the FMI. Sand and silt laminae down to 0.25" can be resolved by the FMI, but cores have laminae down to microscopic scale.

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Slide 35 (Page 37)
I would like to acknowledge the interdisciplinary team and intra-company teams that made this exciting work possible--from Phillips, particularly our Bartlesville Seismic Processing, group, and the other contributions from Anadarko and Amoco.
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