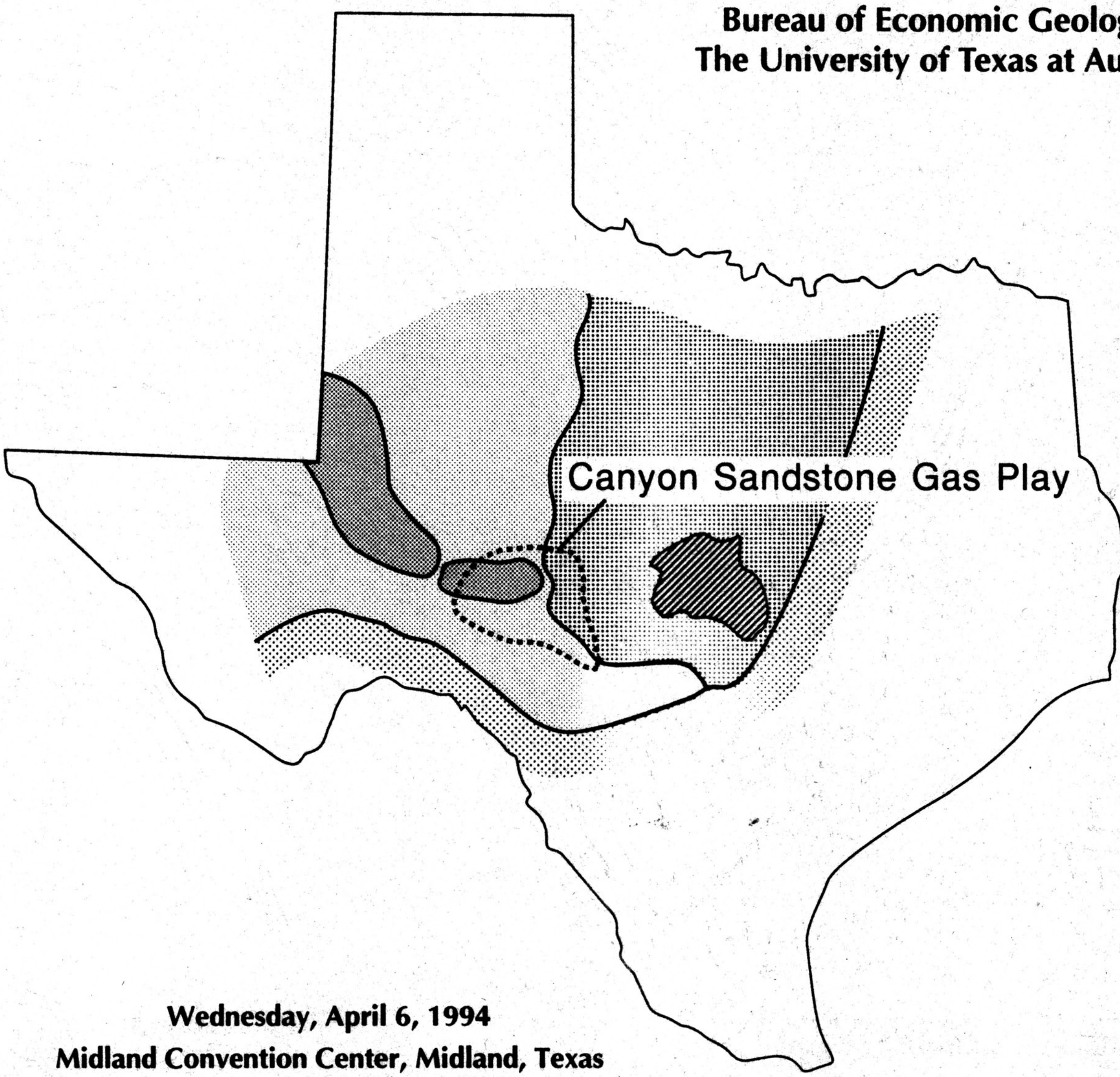
Geology and Production Aspects of a Stratigraphically Complex Natural Gas Play Canyon Sandstone, Val Verde Basin, Texas

A Technology Transfer Seminar sponsored by

GRI Gas Research Institute
West Texas Geological Society
and
Bureau of Economic Geology
The University of Texas at Austin



Wednesday, April 6, 1994
Midland Convention Center, Midland, Texas

Geology and Production Aspects of a Stratigraphically Complex Natural Gas Play Canyon Sandstone, Val Verde Basin, Texas

A Technology Transfer Seminar

Agenda

9:00 – 10:40	
	Introduction and Objectives
	Perspective on Tight Gas Sands: Geological Characteristics of Major Low-Permeability Sandstone Gas Reservoirs in the Continental United States
	Overview of Canyon Sandstone Geology and Engineering
	Regional Tectonic and Stratigraphic Framework of the Val Verde Basin
10:20 – 10:40	Canyon Core Display and Coffee Break
10:40 – 12:00	
	Submarine Fan Model and Mapping Methods Applied to Canyon Sandstone
	Stratigraphy and Productivity of Ozona Canyon Sandstone, Crockett County
	Ozona Canyon Sandstone Composition and Diagenesis
	Summary of Ozona Canyon Natural Fractures
12:00 – 1:00	Hosted Lucheon
1:00 – 2:45	
	Stratigraphy and Productivity of Sonora Canyon Sandstone, Sutton County
	Diagenesis and Reservoir Quality of Sonora Canyon Sandstone
	Natural Fractures, Sonora Canyon
2:45 – 3:10	Canyon Core Display and Coffee Break
3:10 – 4:00	
	Stress Measurements and Summary of GRI Cooperative Well Database
	Review of Operator Survey Results Identification of Development Challenges

INTRODUCTION AND OBJECTIVES

Presented by:

Stephen E. Laubach

Bureau of Economic Geology

The University of Texas at Austin

Austin, Texas

GRI GEOLOGIC RESEARCH OBJECTIVES

- Focus on Increased Understanding of Complex Low-Permeability Reservoirs to Enable Greater Recovery of Gas

- Provide Geologic Data to Integrate with Petrophysics, Reservoir Engineering, and Hydraulic Fracture Modeling

- Develop Insights, Methods, and Technologies Applicable to Broad Spectrum of Complex Sandstone Reservoirs

WORKSHOP OUTLINE I

Perspective on Tight Gas Sandstones

Overview of Canyon Sandstone Play

Regional Framework

Ozona Canyon Stratigraphy

Ozona Canyon Diagenesis & Fractures

Core Display

WORKSHOP OUTLINE II

Sonora Canyon Stratigraphy

Sonora Canyon Diagenesis & Fractures

Stress Directions

GRI Cooperative Well Engineering Data

Review of Survey Results

Challenges

PERSPECTIVE ON TIGHT GAS SANDS: GEOLOGICAL CHARACTERISTICS OF MAJOR LOW-PERMEABILITY SANDSTONE GAS RESERVOIRS IN THE CONTINENTAL UNITED STATES

Presented by:

Shirley P. Dutton

Bureau of Economic Geology

The University of Texas at Austin

Austin, Texas

OVERVIEW OF CANYON SANDSTONE GEOLOGY AND ENGINEERING

Presented by:

H. Scott Hamlin

Bureau of Economic Geology

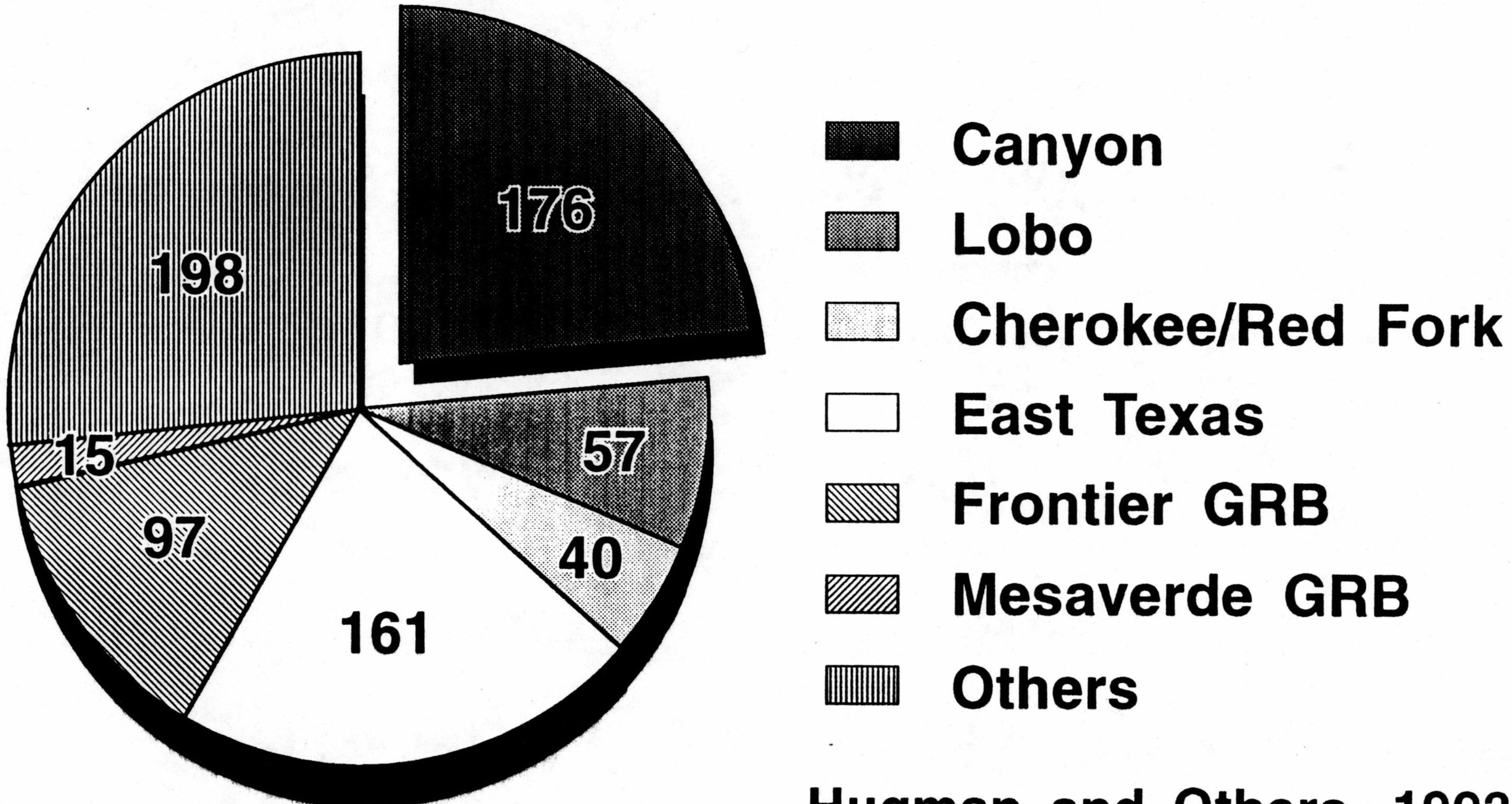
The University of Texas at Austin

Austin, Texas

MAJOR LOW-PERMEABILITY GAS PLAY IN WEST TEXAS

- 2.2 Tcf Cumulative Production
- 2 Tcf Reserves in Existing Wells
- Producing Area Spans 3,800 mi^2

TIGHT GAS SS. NET NEW COMPL. IN 1991

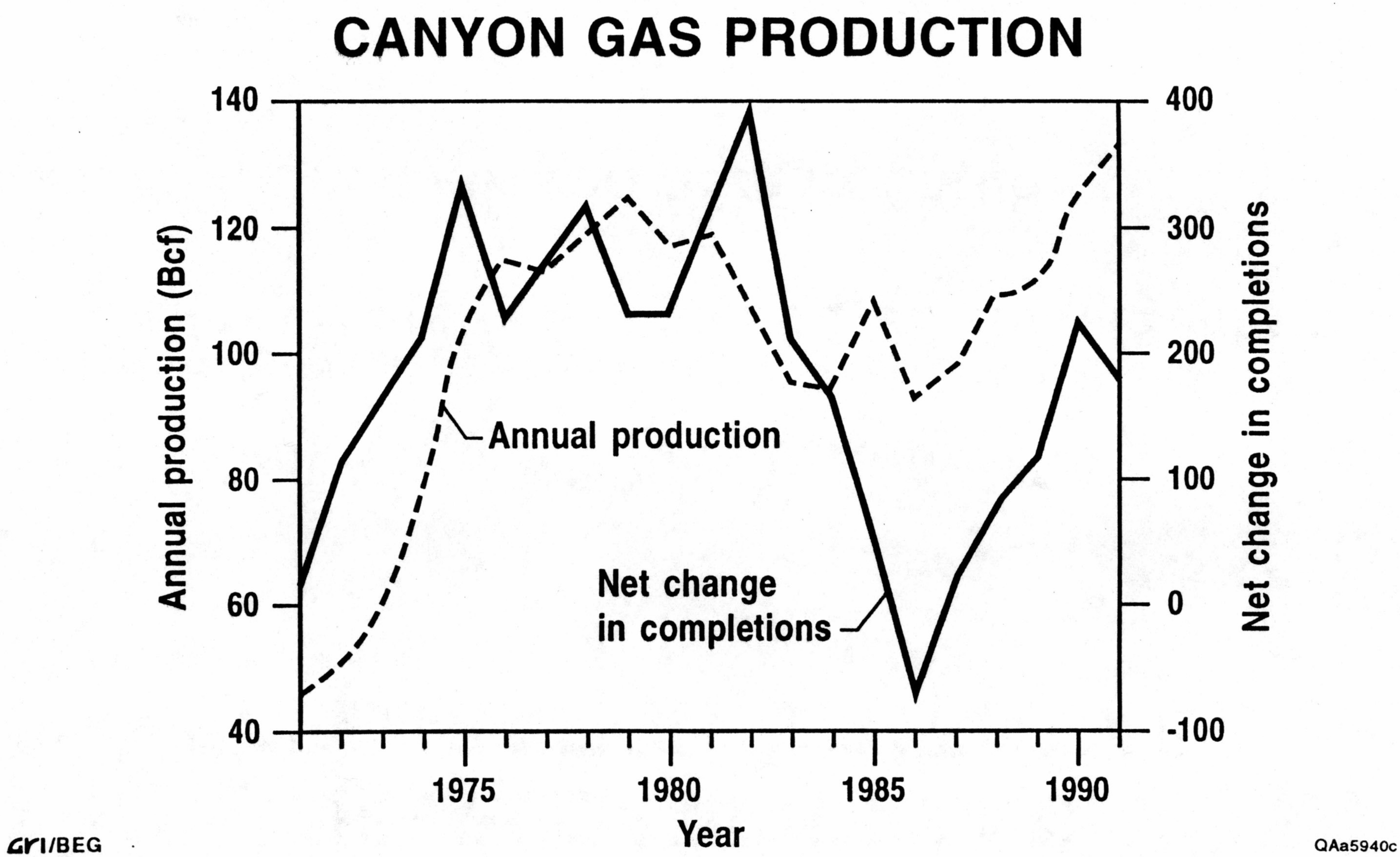


Hugman and Others, 1993

GRI/BEG

Total = 709

QAa6075c


CANYON GAS PRODUCTION
140
120
100
80
60
40
Annual production (Bcf)
400
300
200
100
0
-100
Net change in completions
Annual production
Net change
in completions
1975
1980
1985
1990
Year
GRI/BEG
QAa5940c

DEVELOPMENT AND EXPLORATION POTENTIAL

- Per-Well Recovery Averages 0.7 Bcf
- Drilling Density Averages 1.25 Wells/Section
- Large Undeveloped Area to South

CANYON ECONOMICS

- Variable Productivities
  - 100 to 20,000 Mcf/d IP
  - 0.05 to 5 Bcf Recovery per Well

- Fixed Expenses: Well Completion, Stimulation
  - $175,00 to $440,000 per Well

- 0.3 Bcf Production per Well to Cover Well Costs

- 0.7 Bcf Average Well Recovery

- Geologic Targeting can Increase per Well Recovery

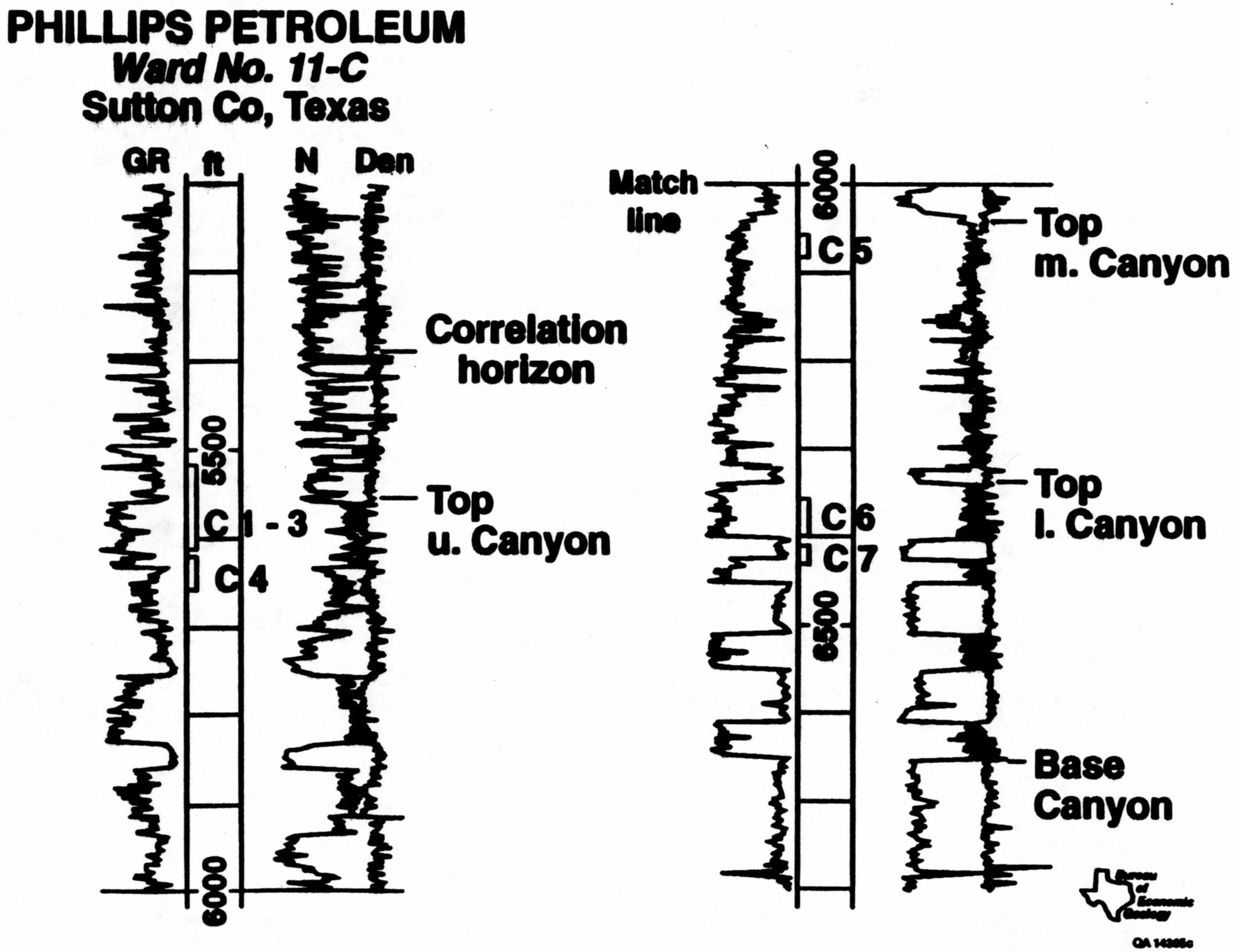
GEOLOGICALLY COMPLEX LOW-PERMEABILITY RESERVOIRS

- Discontinuous, Laminated Stratigraphy
- Extensive Diagenetic Modification
- Widespread Natural Fractures

CANYON RESERVOIR PROPERTIES

Depth:	2,500 to 8,500 ft
Temperature:	100° to 185°F
Pressure:	500 to 3,500 psi
Gross Sandstone:	100 to 1,300 ft
Net Pay:	20 to 300 ft
Porosity:	1 to 15%
In Situ Permeability:	0.001 to 0.03 md
Water Saturation:	> 20%
Trap:	Porosity Pinchout

CANYON SANDSTONE TYPE LOG



REGIONAL TECTONIC AND STRATIGRAPHIC FRAMEWORK OF THE VAL VERDE BASIN

Presented by:

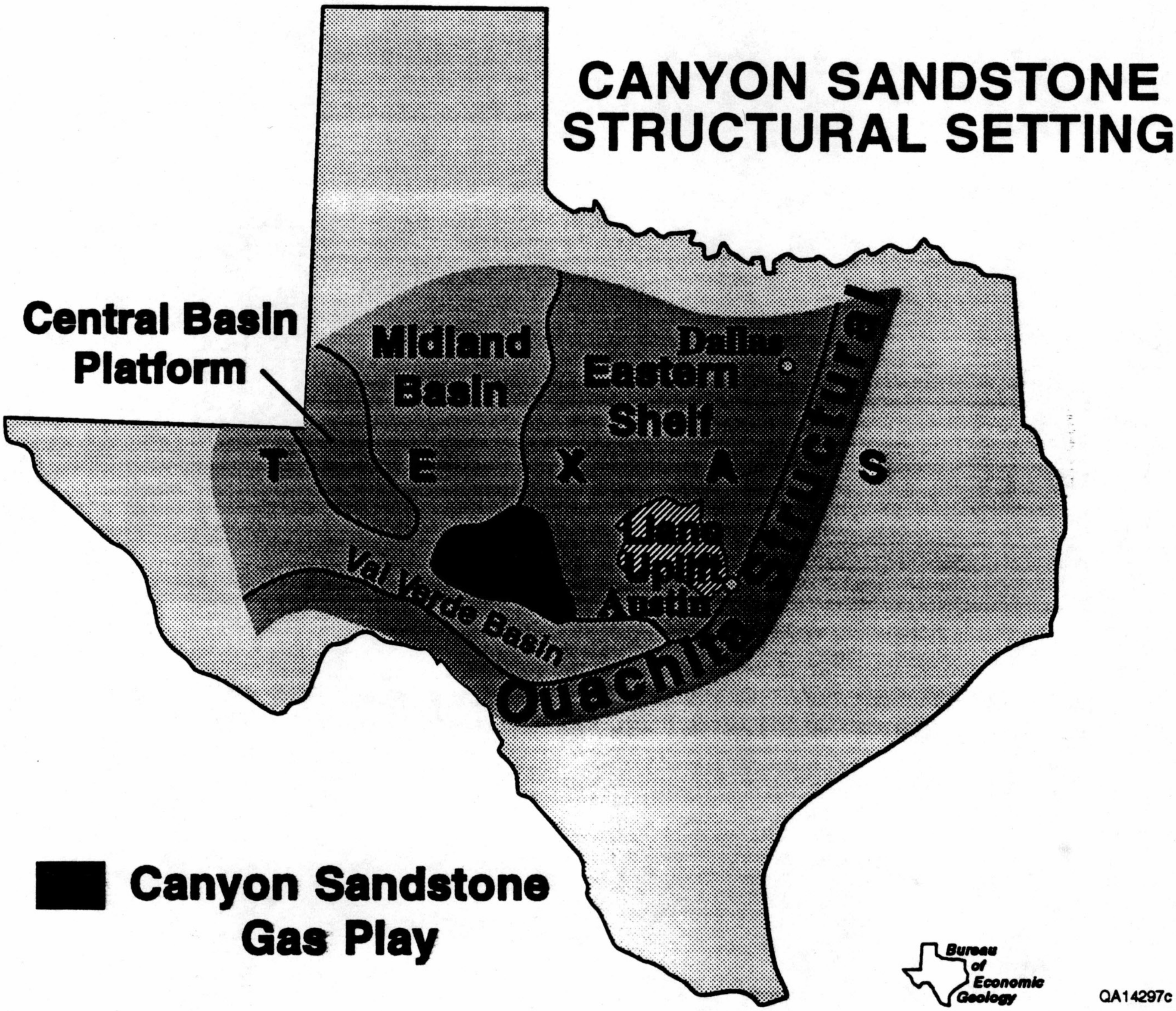
H. Scott Hamlin

Bureau of Economic Geology

The University of Texas at Austin

Austin, Texas

CANYON SANDSTONE STRUCTURAL SETTING



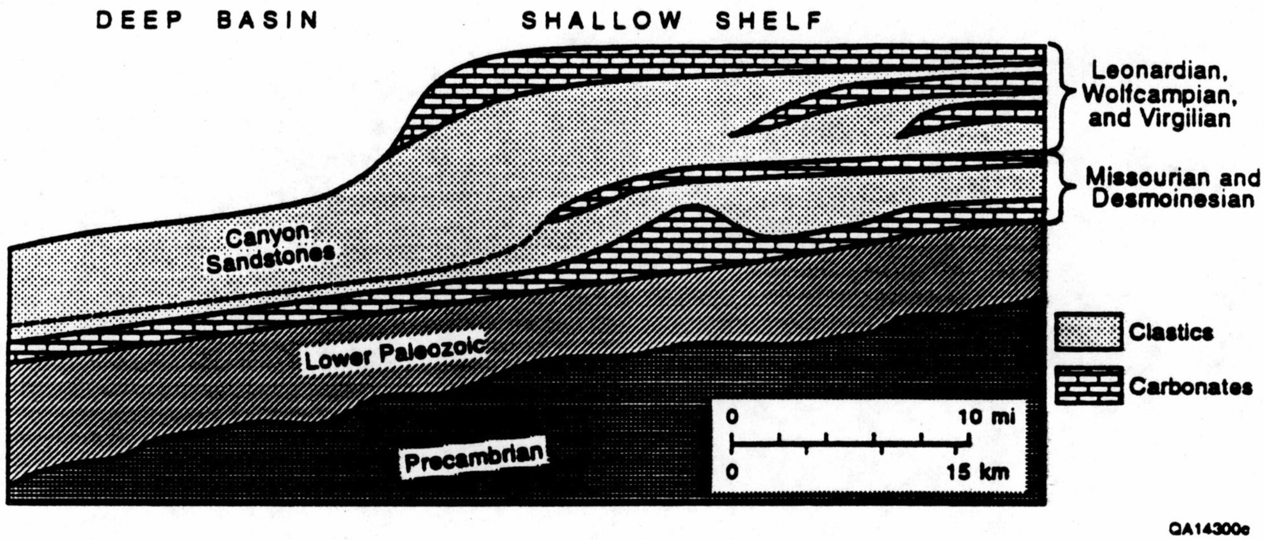
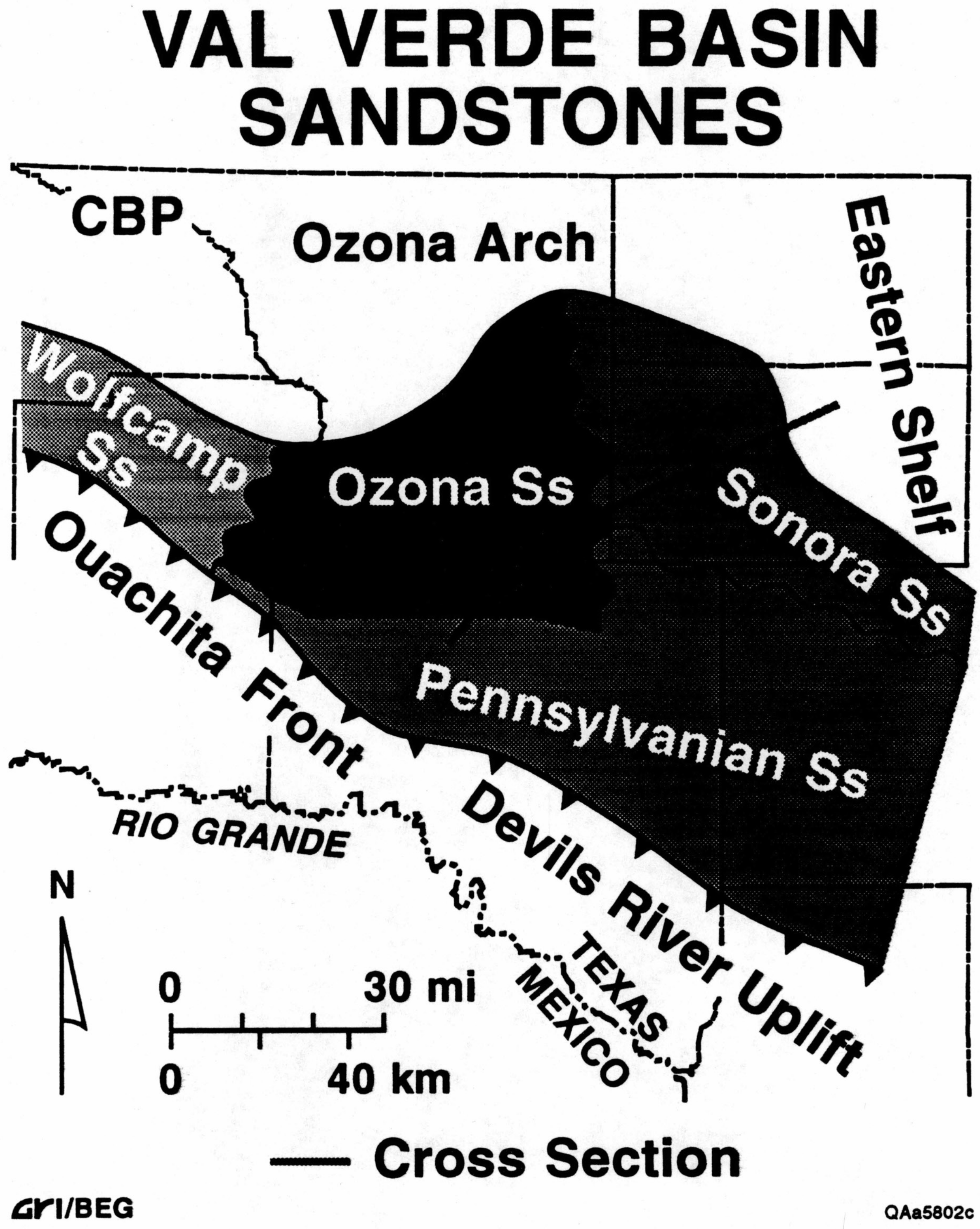


Figure Schematic cross section showing Late Pennsylvanian-Early Permian depositional topography, northeastern Val Verde Basin. Modified from Rall and Rall (1958).


VAL VERDE BASIN
SANDSTONES
CBP
Ozona Arch
Eastern Shelf
Wolfcamp Ss
Ozona Ss
Sonora Ss
Ouachita Front
Pennsylvanian Ss
Devils River Uplift
RIO GRANDE
TEXAS
MEXICO
N
0
30 mi
0
40 km
Cross Section
GRI/BEG
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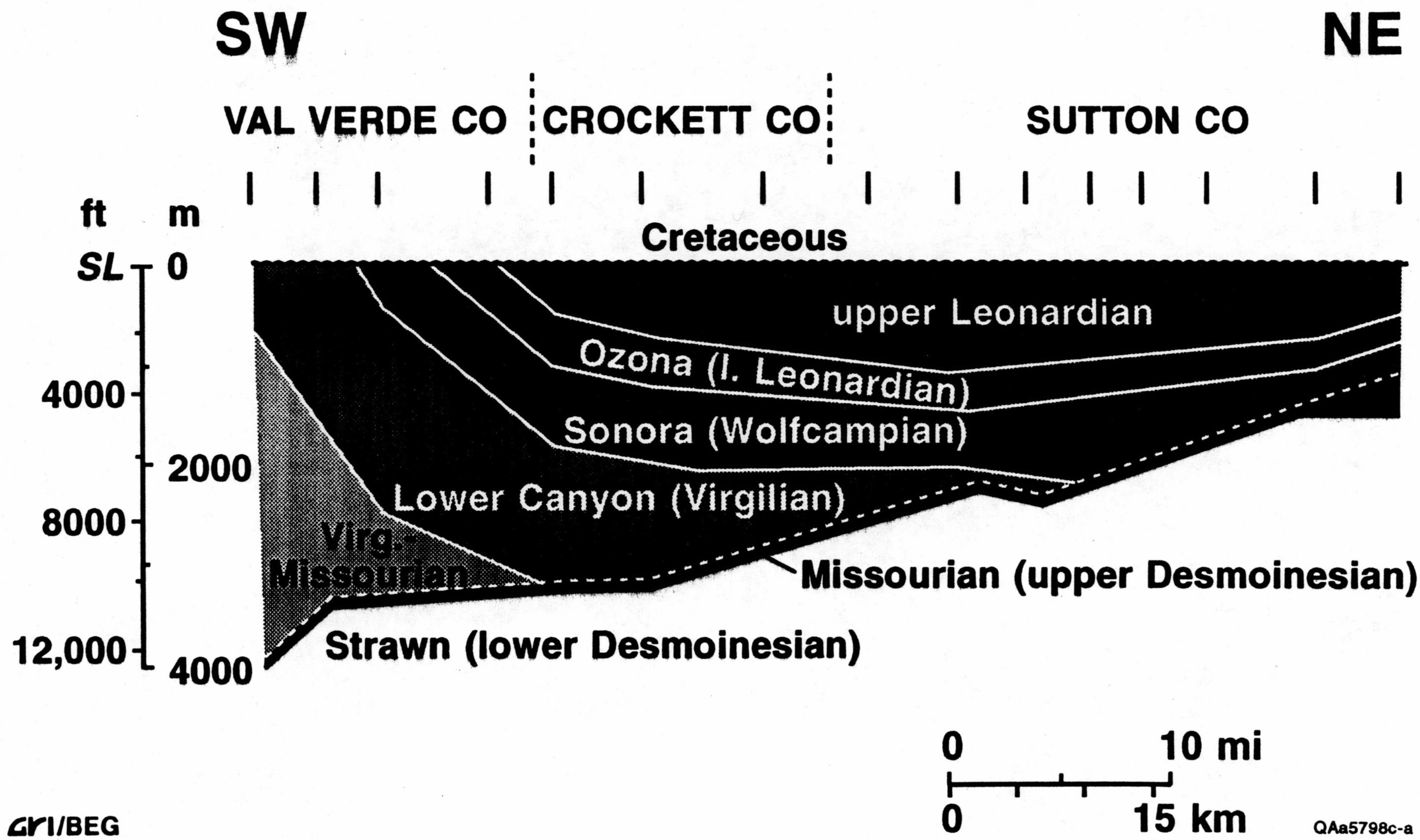
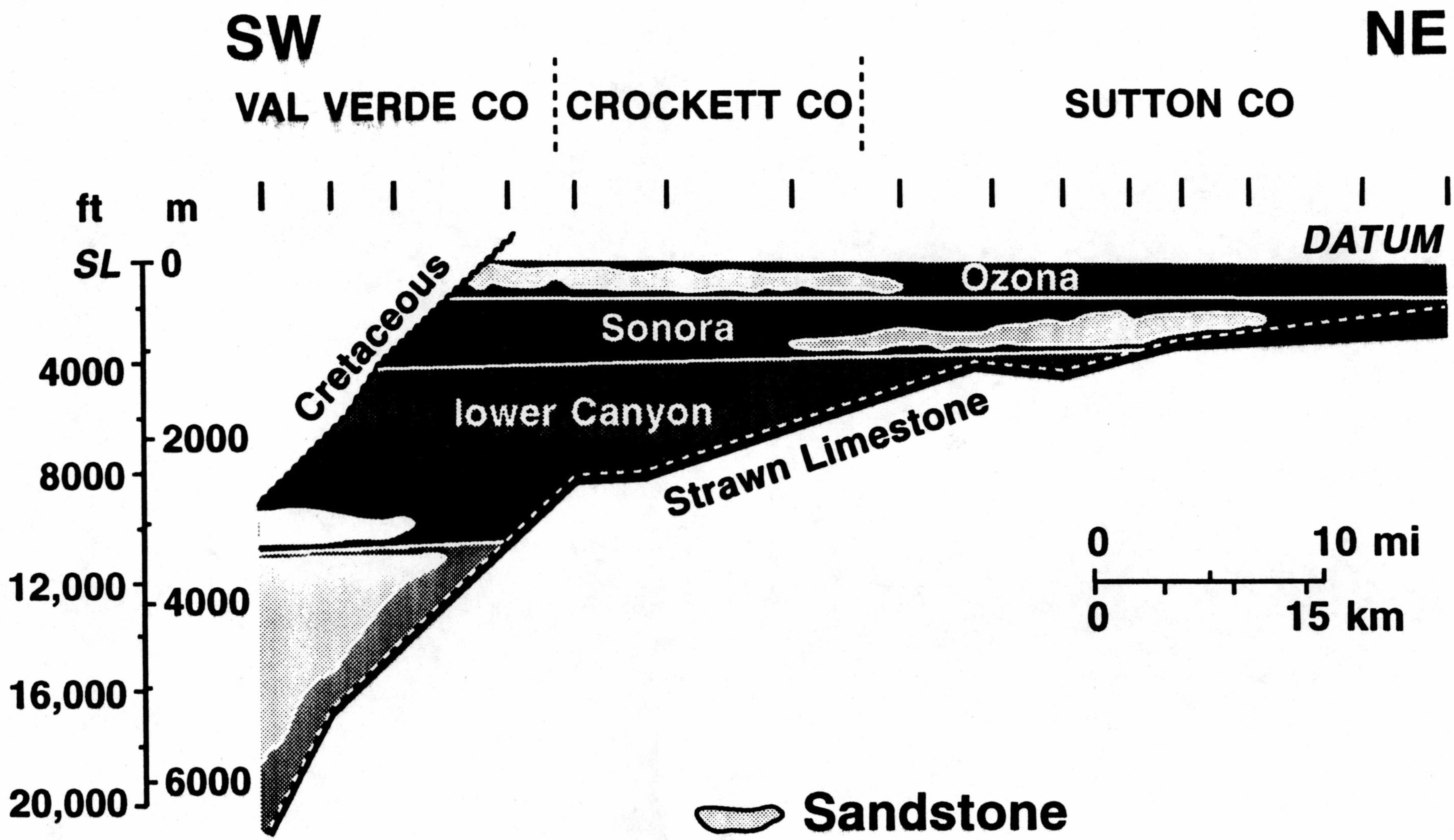


SW
NE
VAL VERDE CO
CROCKETT CO
SUTTON CO
ft
m
Cretaceous
SL
0
4000
2000
8000
12,000
4000
upper Leonardian
Ozona (l. Leonardian)
Sonora (Wolfcampian)
Lower Canyon (Virgilian)
Virg.-Missourian
Missourian (upper Desmoinesian)
Strawn (lower Desmoinesian)
0
10 mi
0
15 km
GRI/BEG
QAa5798c-a



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SUBMARINE FAN MODEL AND MAPPING METHODS APPLIED TO CANYON SANDSTONE

Presented by:

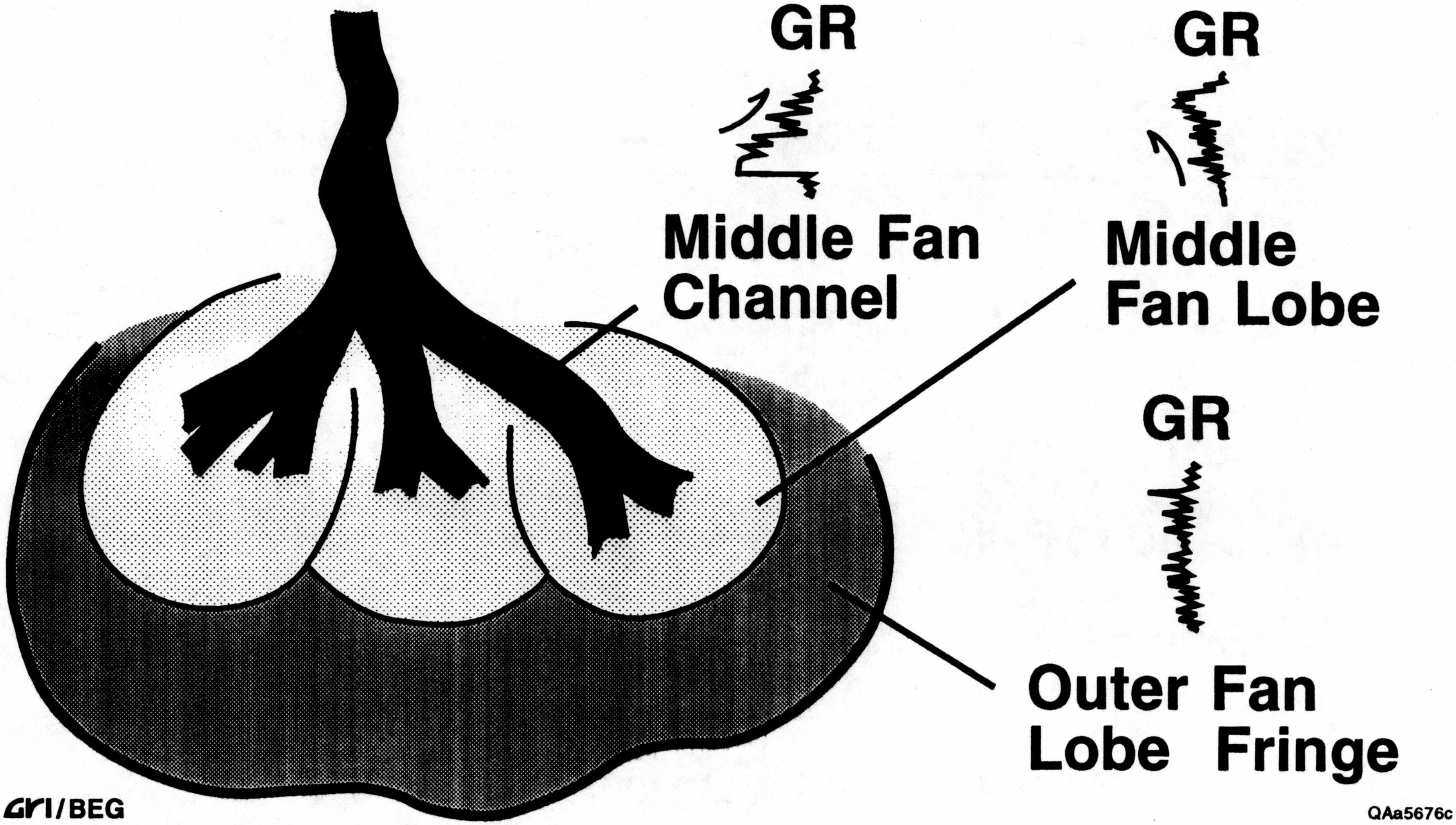
H. Scott Hamlin

Bureau of Economic Geology

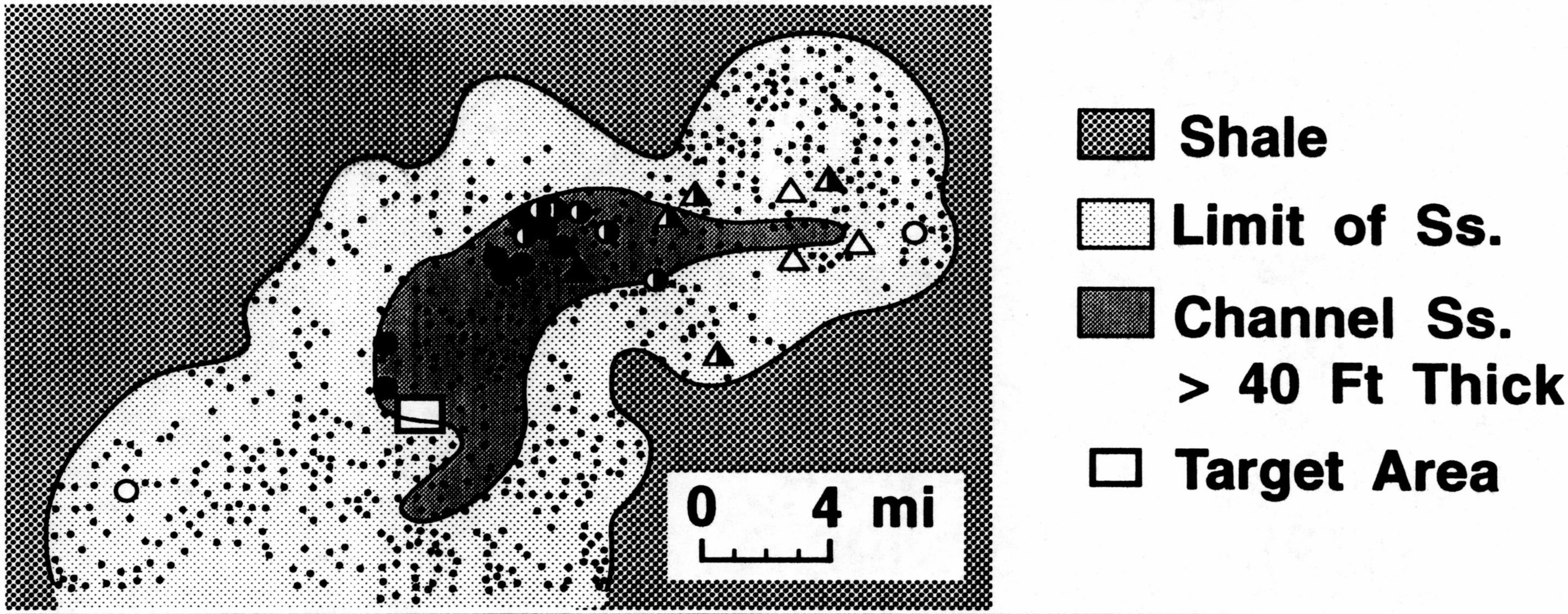
The University of Texas at Austin

Austin, Texas

CANYON SUBMARINE FAN MODEL



OZONA SANDSTONE ZONE 1



Zone 1 Perfs	Zone 1 & 2 Perfs	IP Mcf/d
○	△	< 1000
◐	◭	1000 – 5000
●	▲	> 5000

· Other Gas Wells

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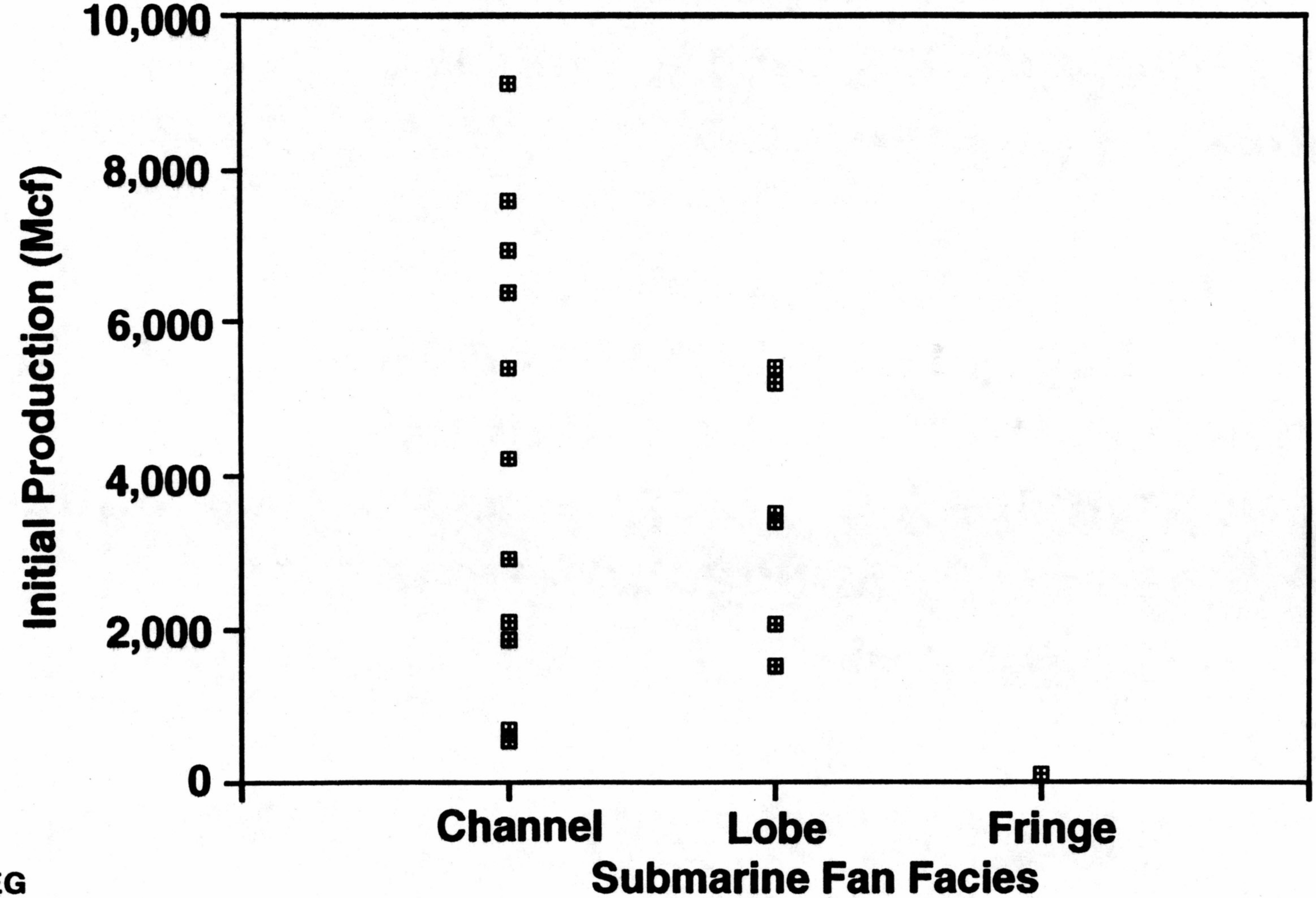
OZONA CANYON ZONE 1
INITIAL PRODUCTION (MCF) VS. FACIES



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CANYON PRODUCTIVITY
LEVELS OF CONTROL

Depositional	**Reservoir Architecture, Initial Porosity and Permeability**
Diagenetic	**Compaction and Cementation Modify Original Porosity and Permeability**
Structural	**Stress and Natural Fractures Complicate Well Completion and Productivity**
Hydrodynamic	**Low Temperatures and Pressures, Variable Water Saturations**
Engineering	**Well Completion and Stimulation Techniques**

STRATIGRAPHY AND PRODUCTIVITY OF OZONA CANYON SANDSTONE, CROCKETT COUNTY

Presented by:

Sigrid J. Clift

Bureau of Economic Geology

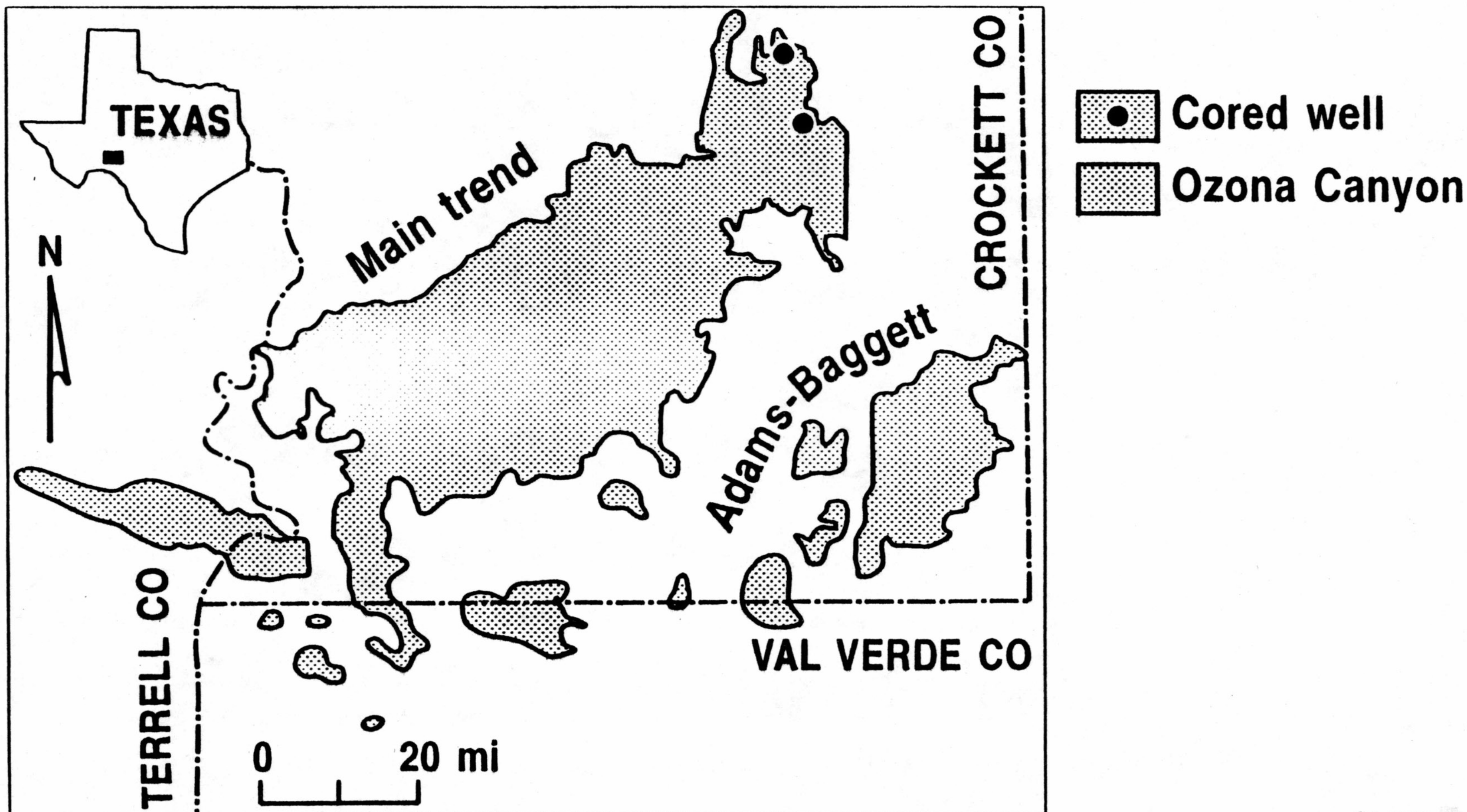
The University of Texas at Austin

Austin, Texas

OZONA CANYON STRATIGRAPHY

- Ozona Producing Trend
- Regional Sandstone Distribution
- Submarine Fan Facies

OZONA CANYON GAS FIELDS



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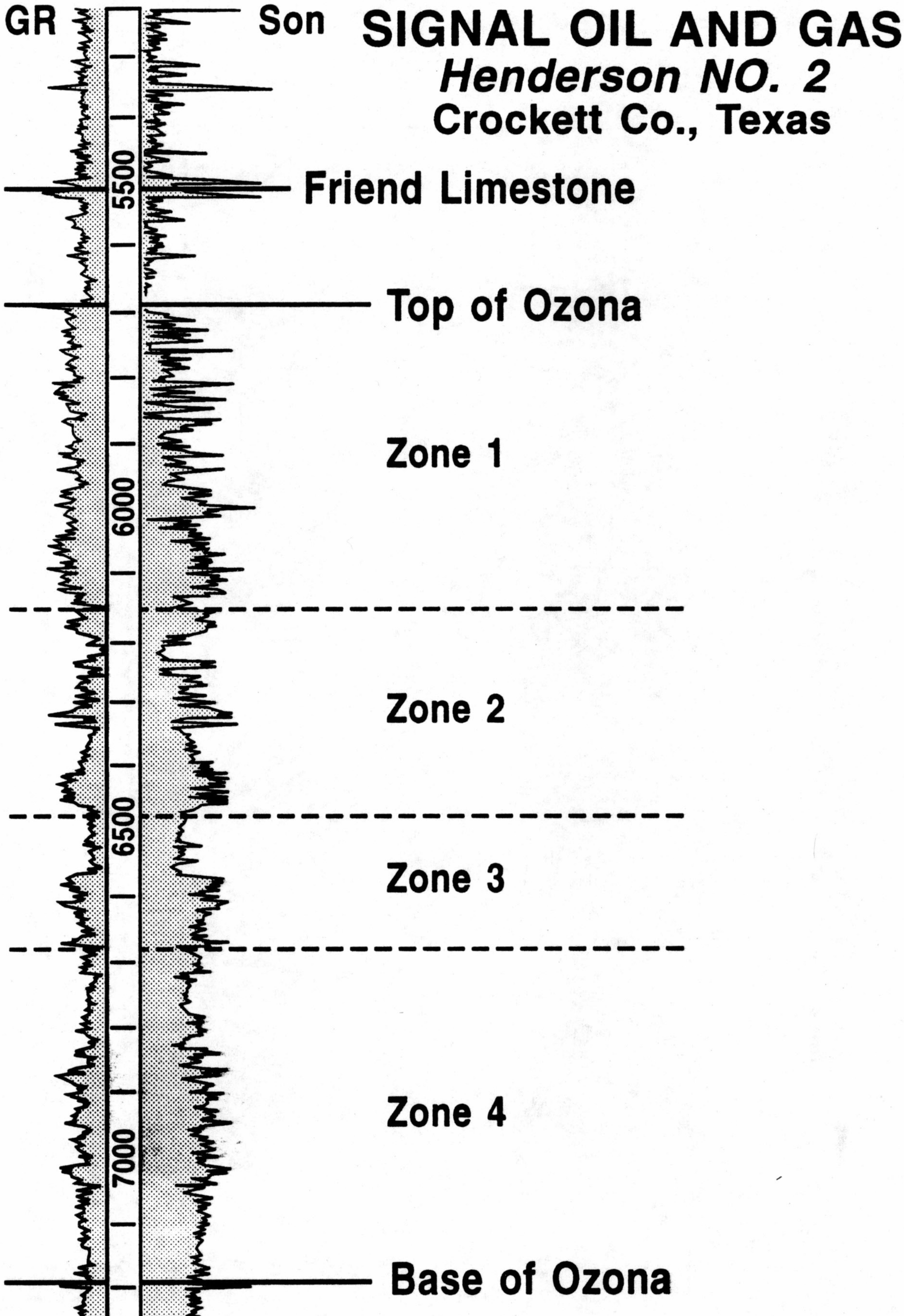
GR
Son
SIGNAL OIL AND GAS
Henderson NO. 2
Crockett Co., Texas
5500
Friend Limestone
Top of Ozona
Zone 1
6000
Zone 2
6500
Zone 3
Zone 4
7000
Base of Ozona
GRI/BEG
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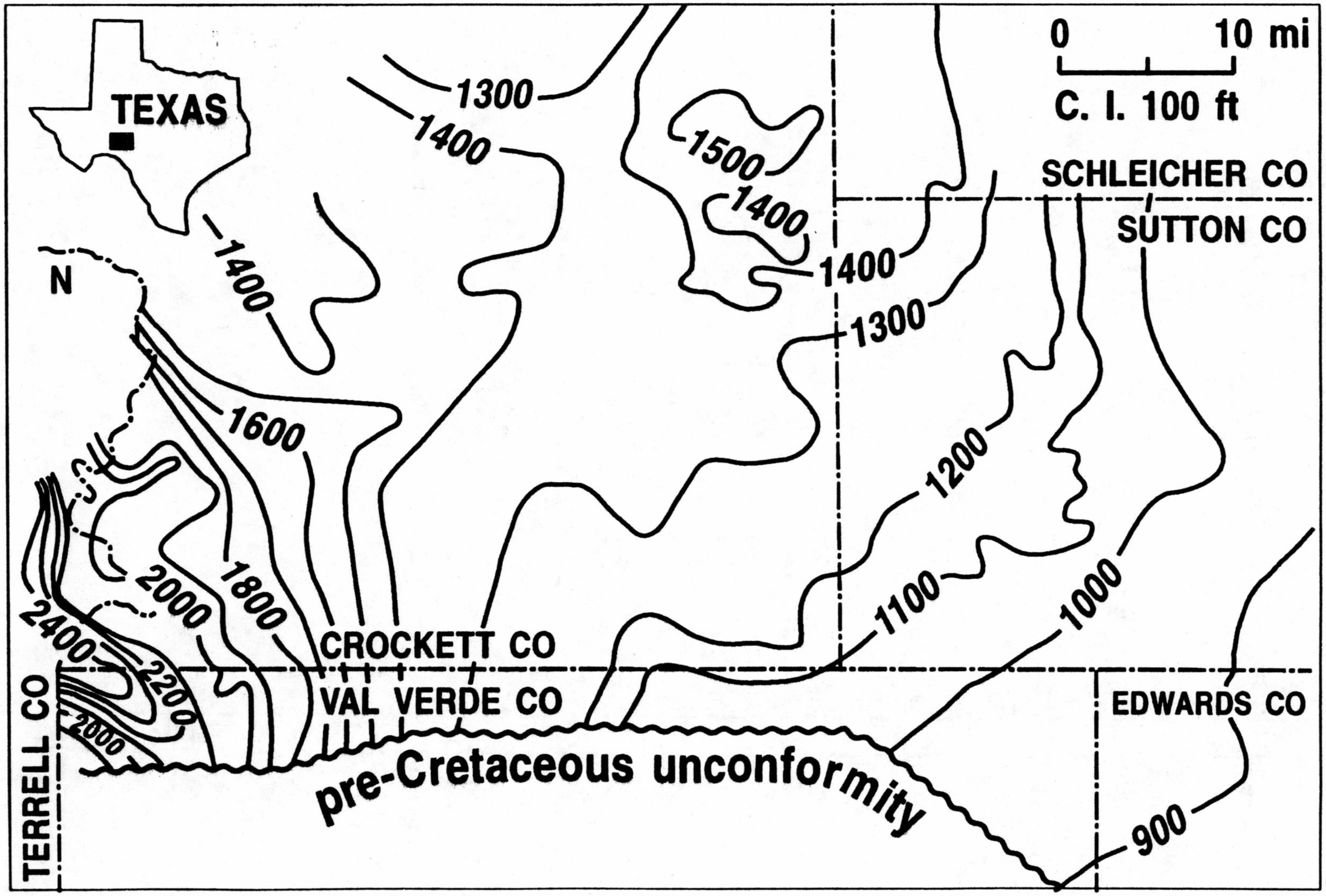
OZONA ISOPACH MAP



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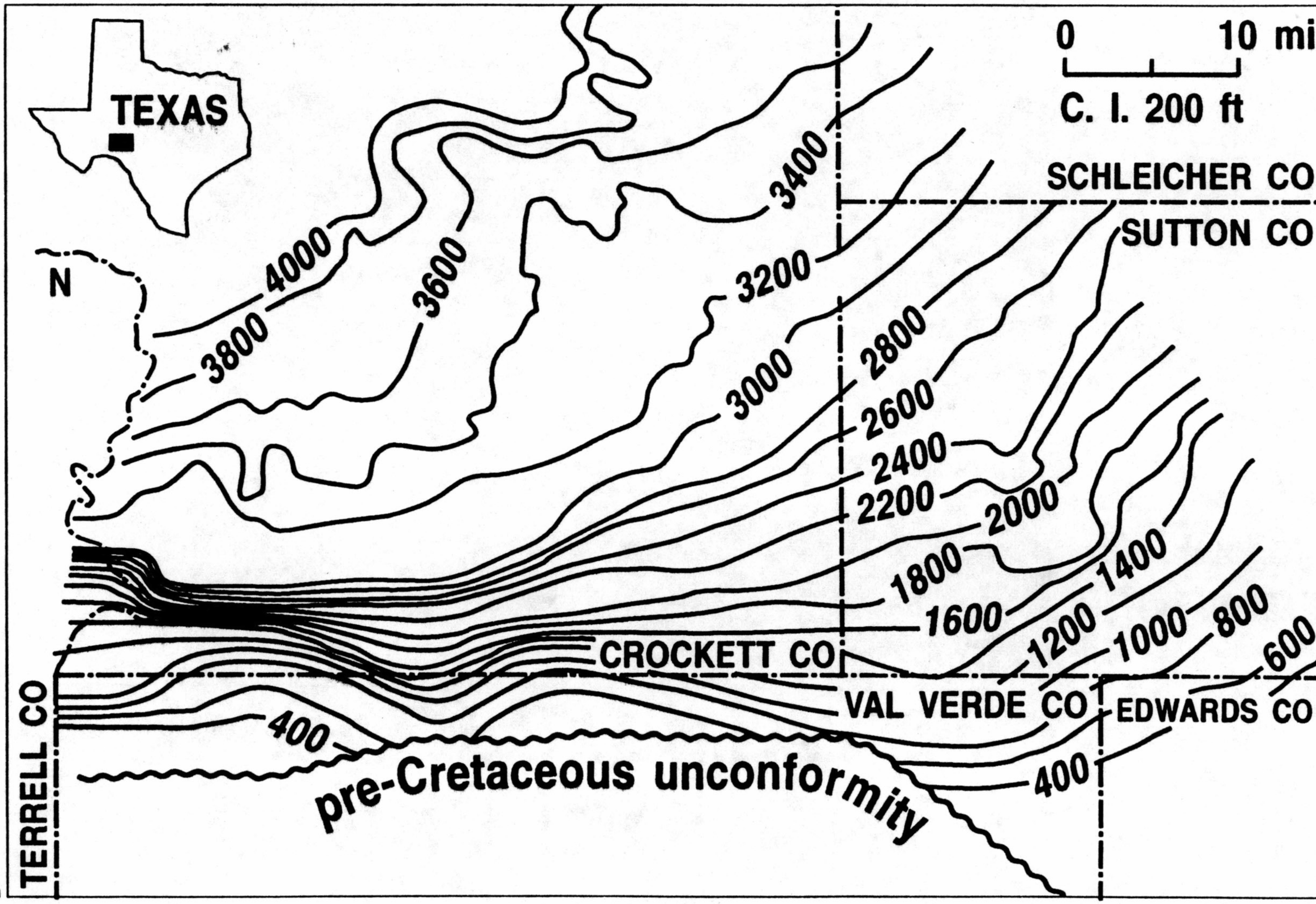
OZONA STRUCTURE MAP



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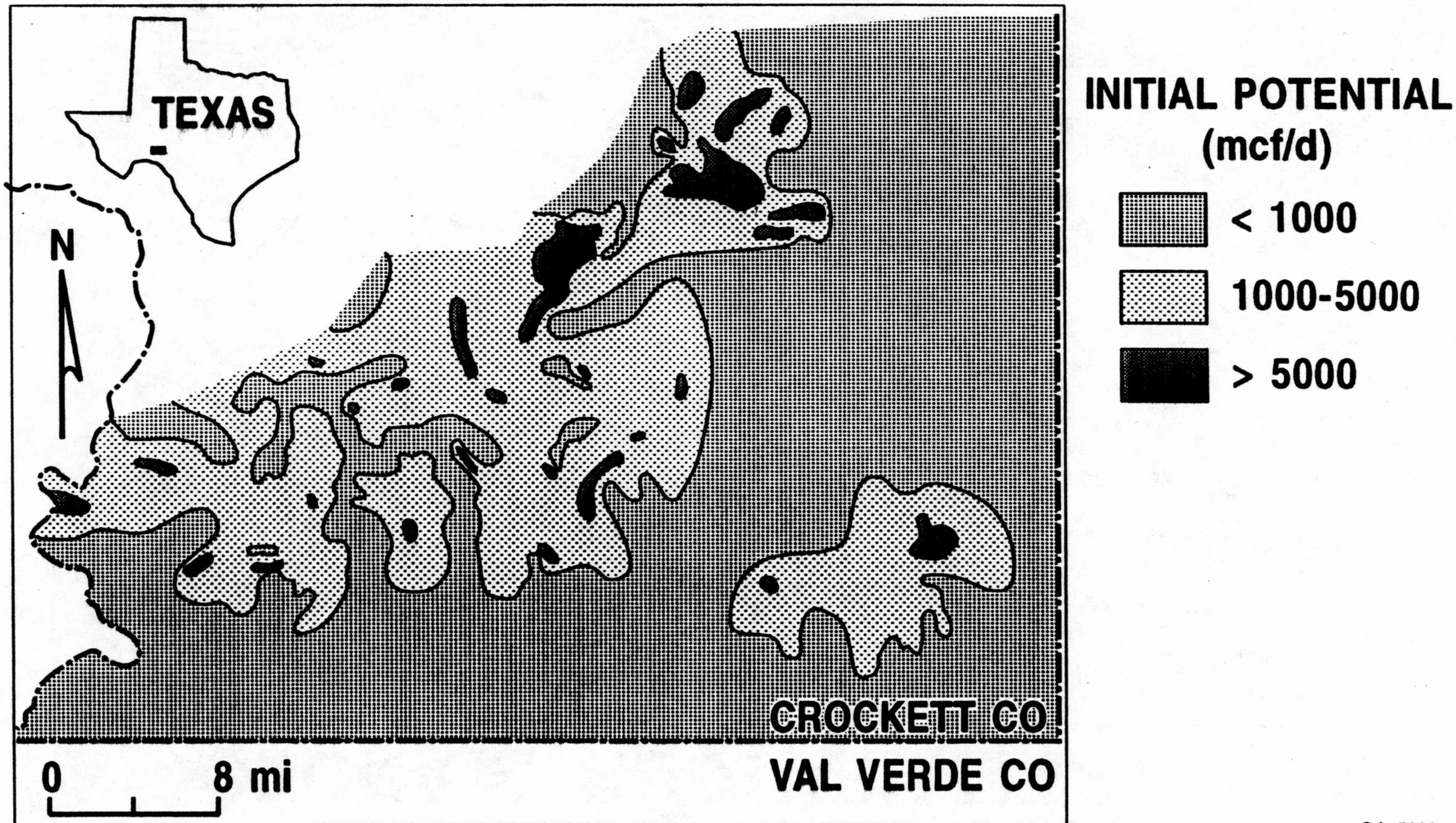
OZONA CANYON INITIAL POTENTIALS



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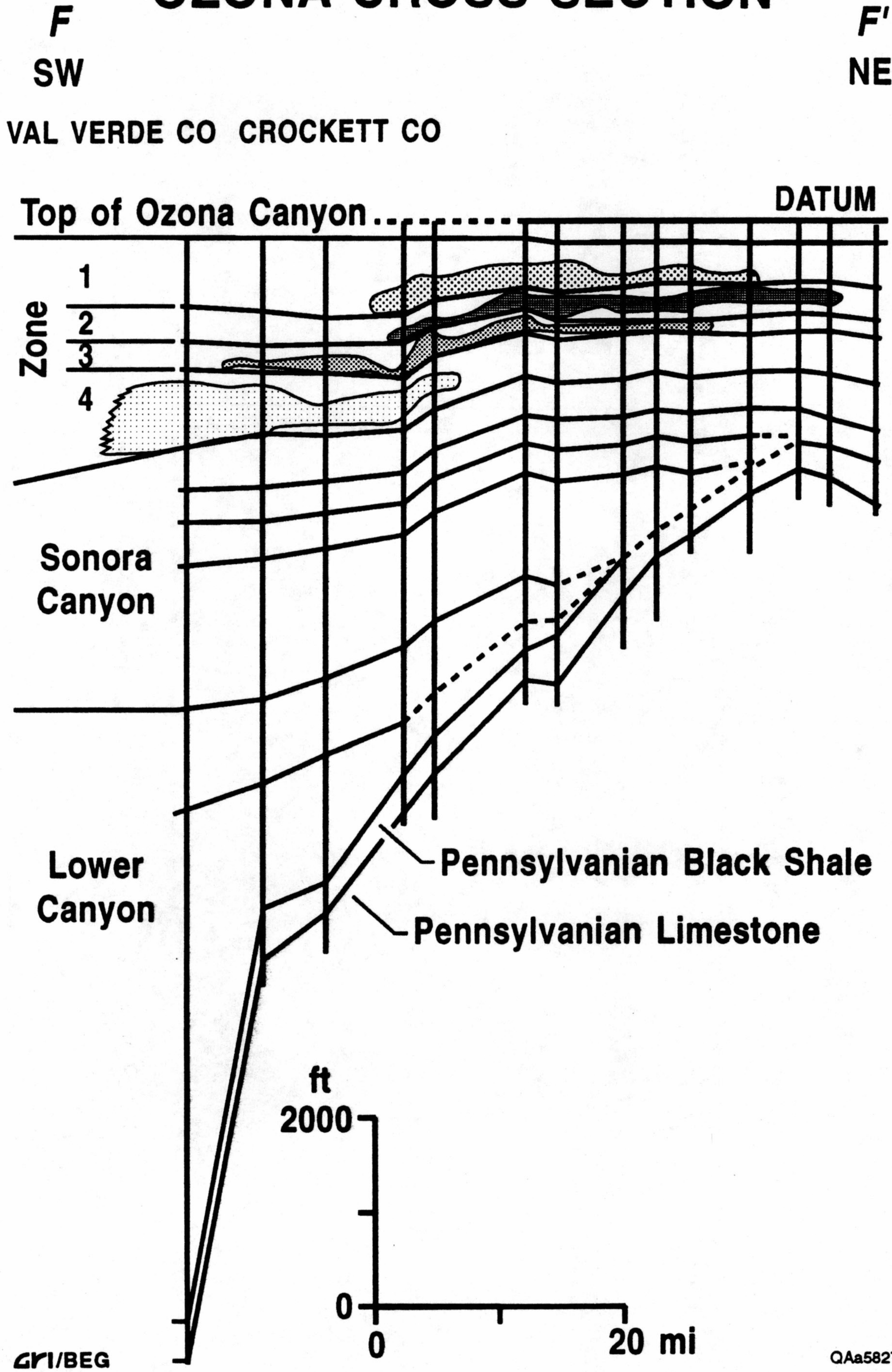
OZONA CROSS SECTION



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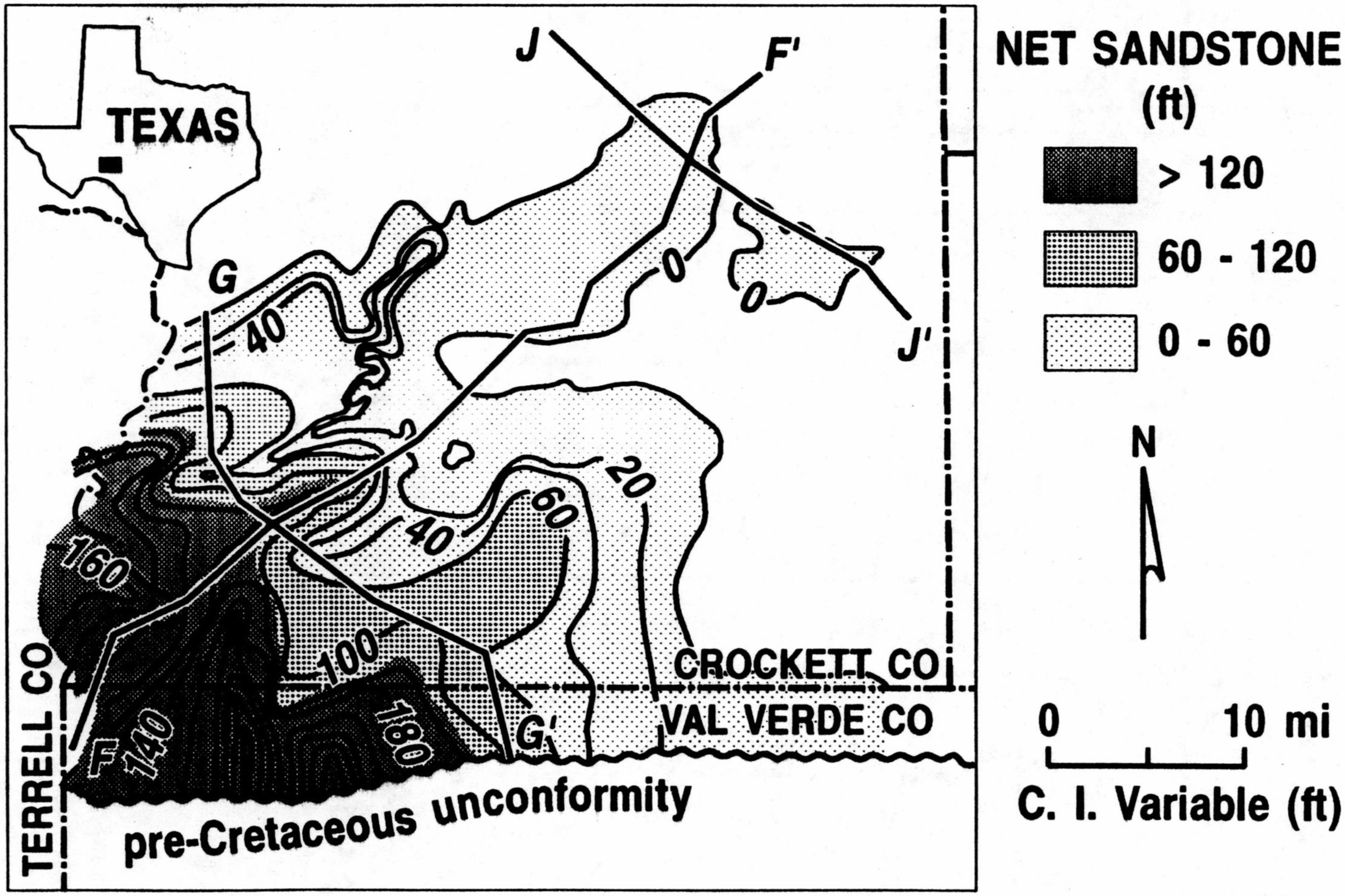
OZONA ZONE 4
NET SANDSTONE



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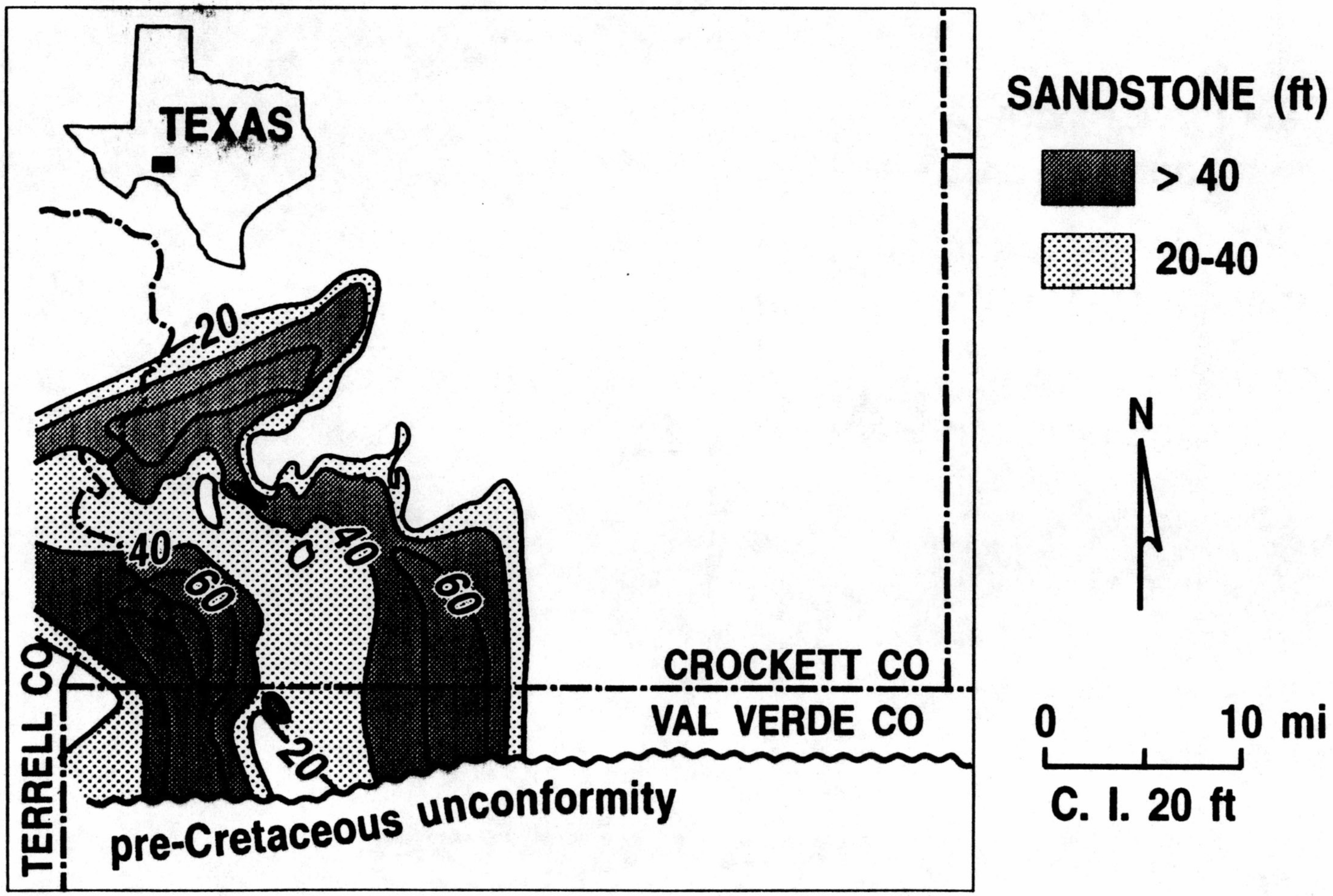
OZONA ZONE 4
MAXIMUM SANDSTONE



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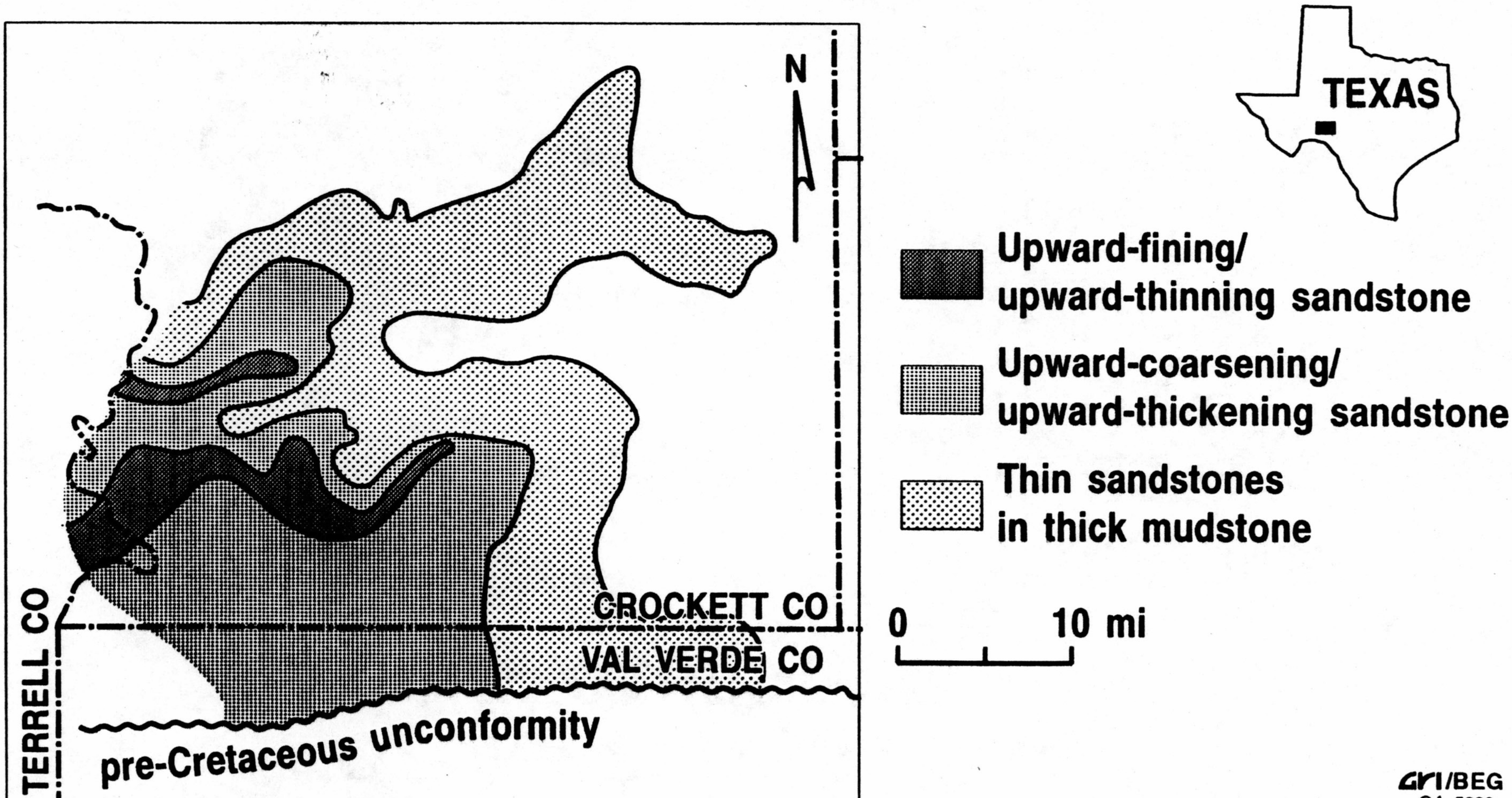
OZONA ZONE 4
LOG FACIES



GRI/BEG
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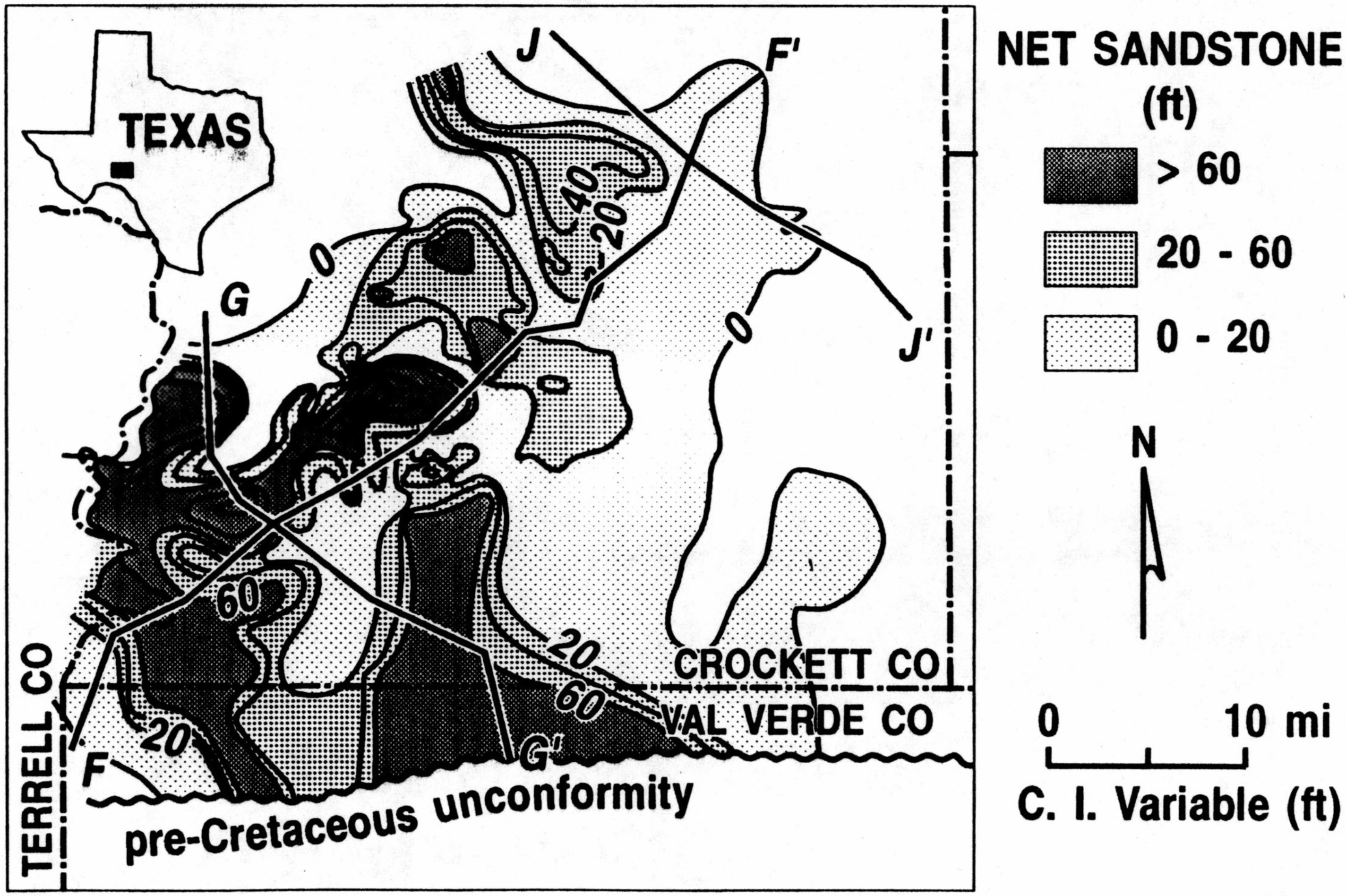
OZONA ZONE 3
NET SANDSTONE



GRI/BEG

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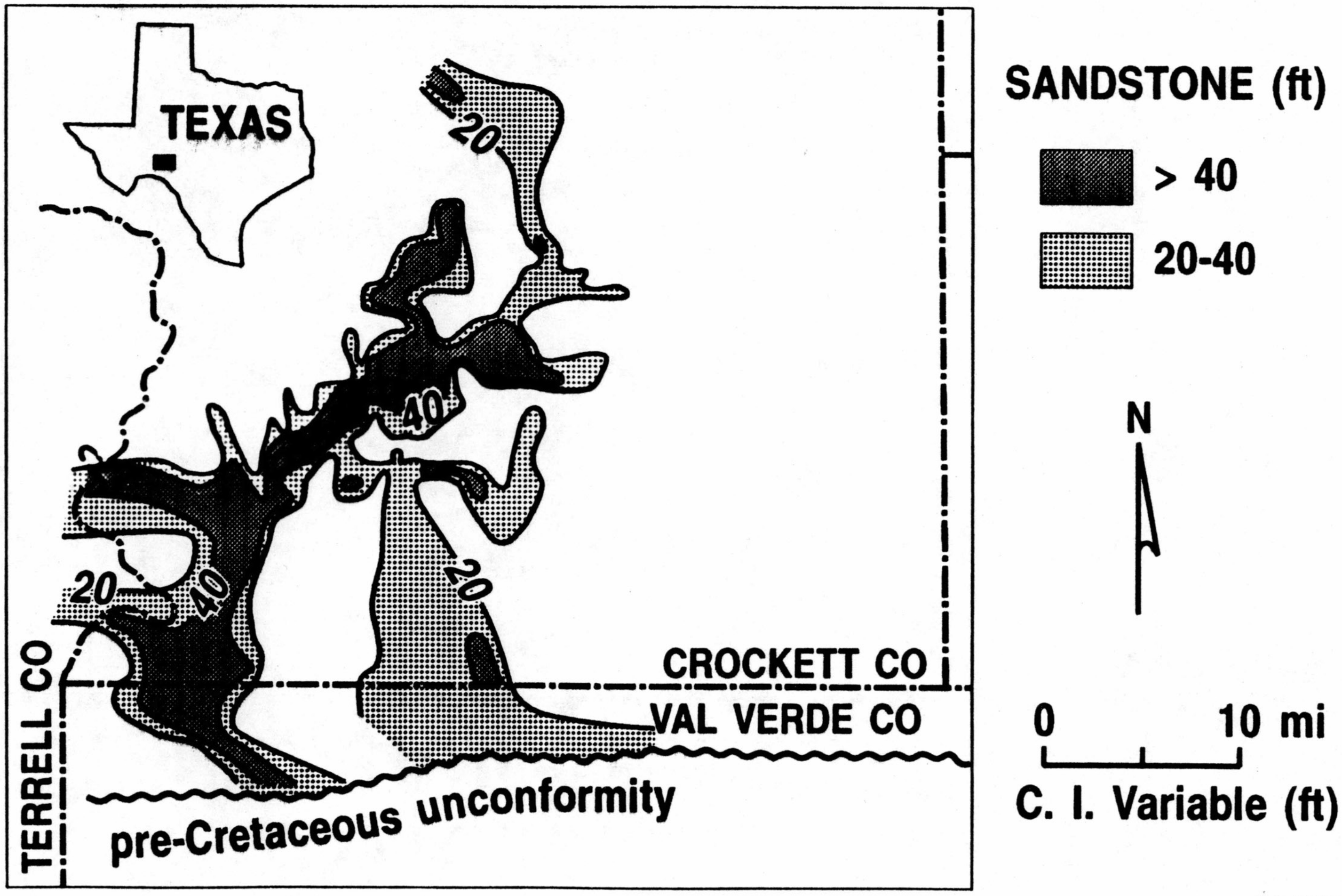
OZONA ZONE 3
MAXIMUM SANDSTONE



GRI/BEG

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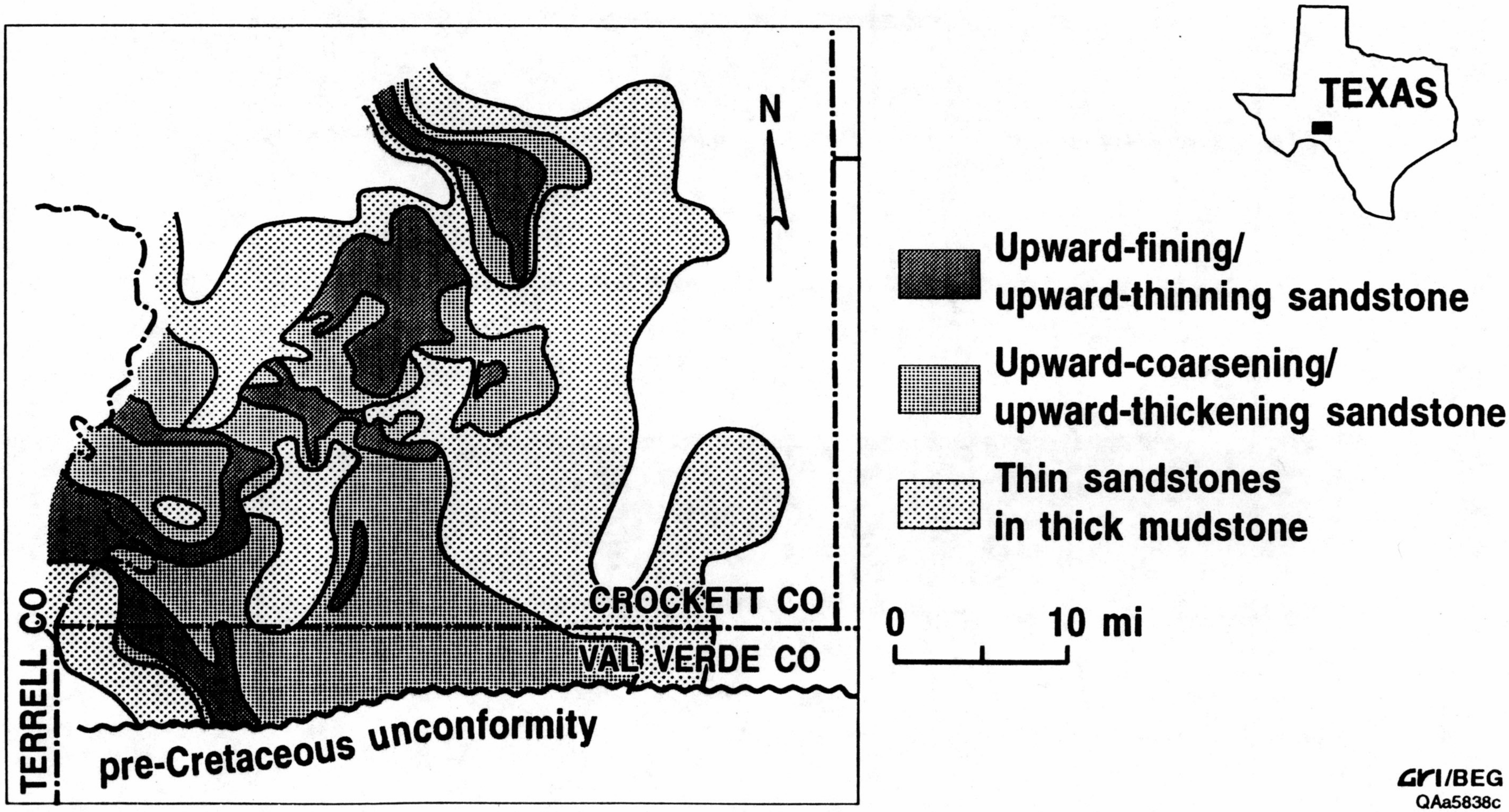
OZONA ZONE 3
LOG FACIES



GRI/BEG
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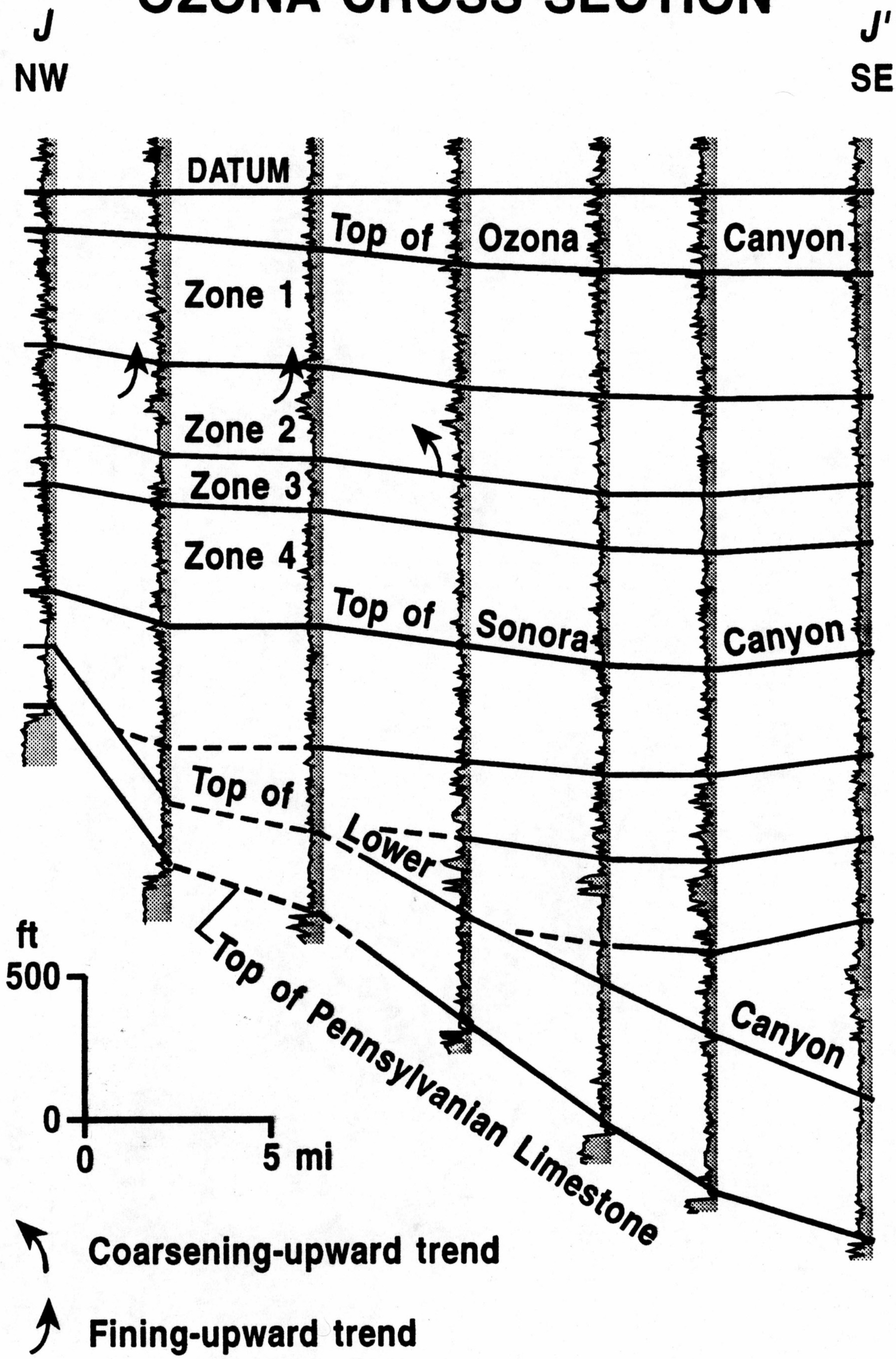
OZONA CROSS SECTION



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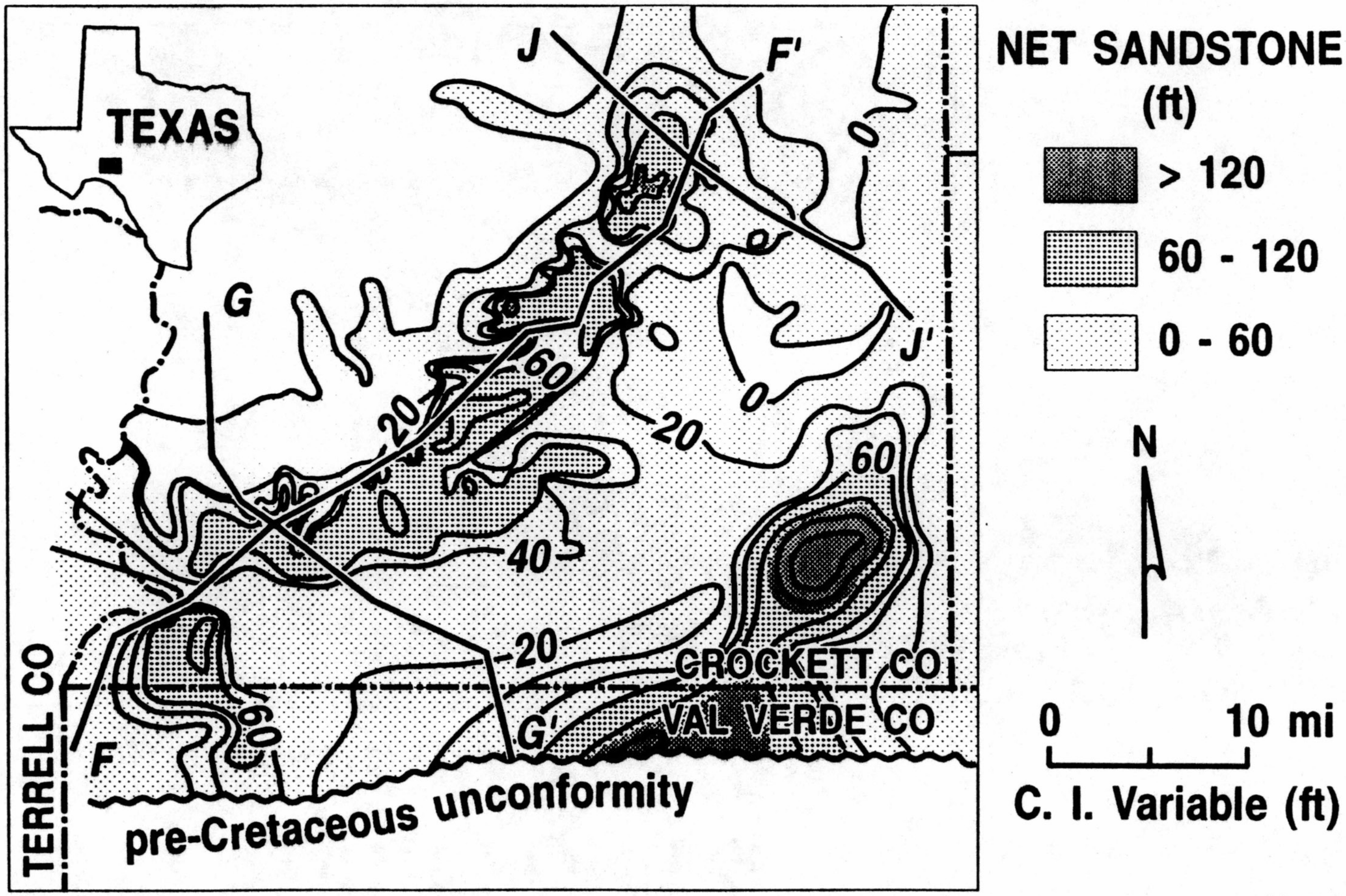
OZONA ZONE 2
NET SANDSTONE



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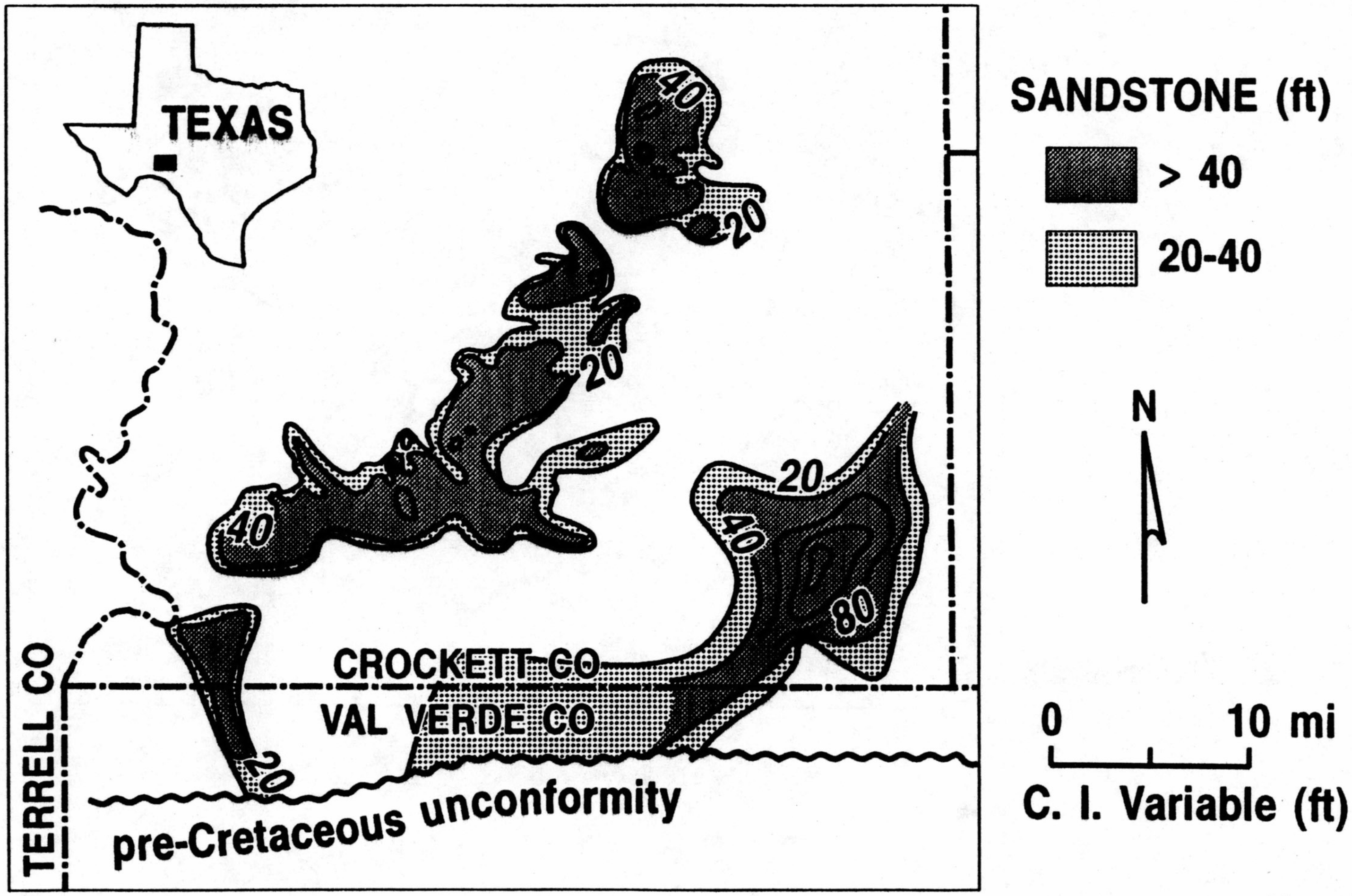
OZONA ZONE 2
MAXIMUM SANDSTONE



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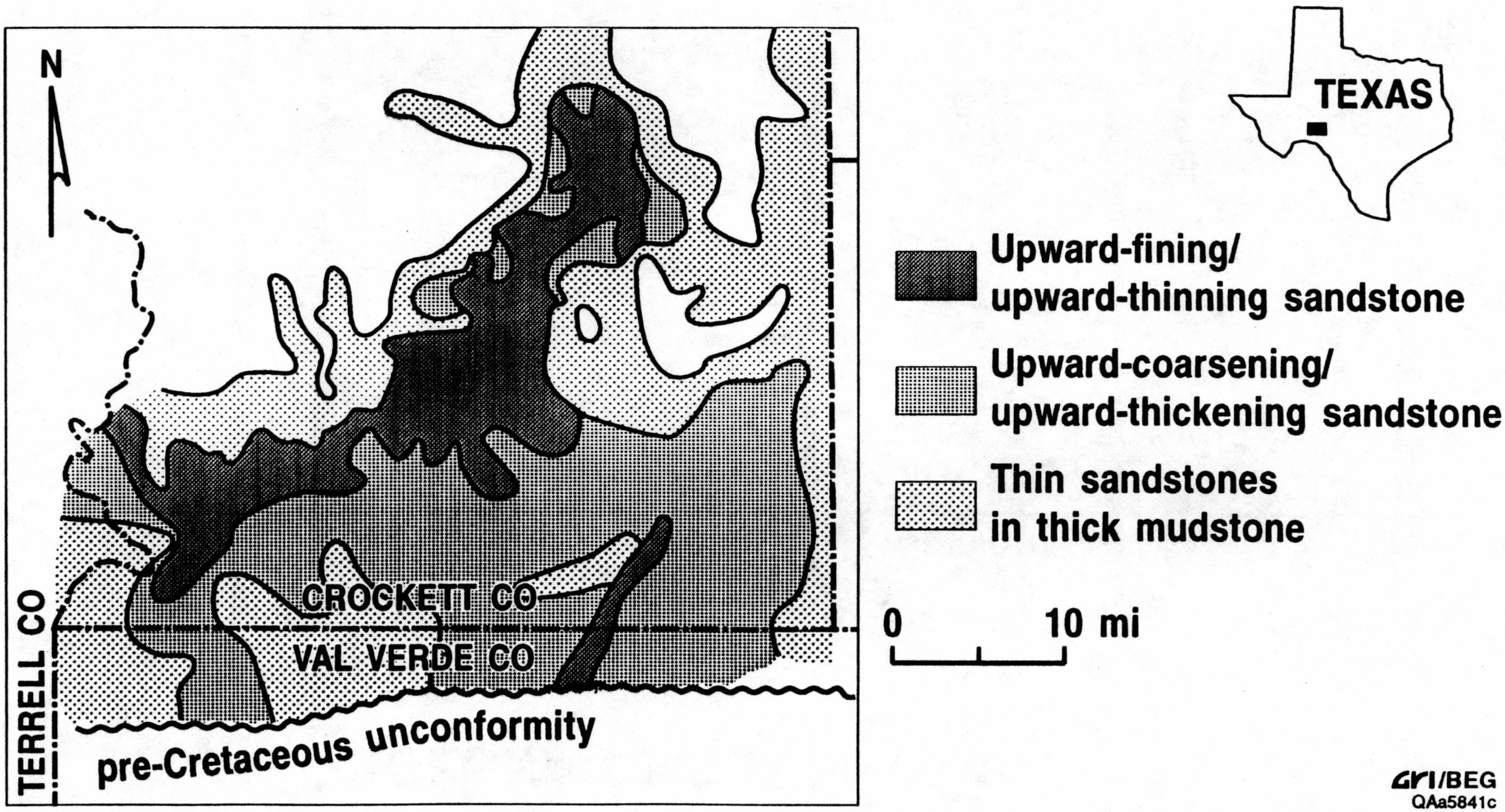
OZONA ZONE 2
LOG FACIES



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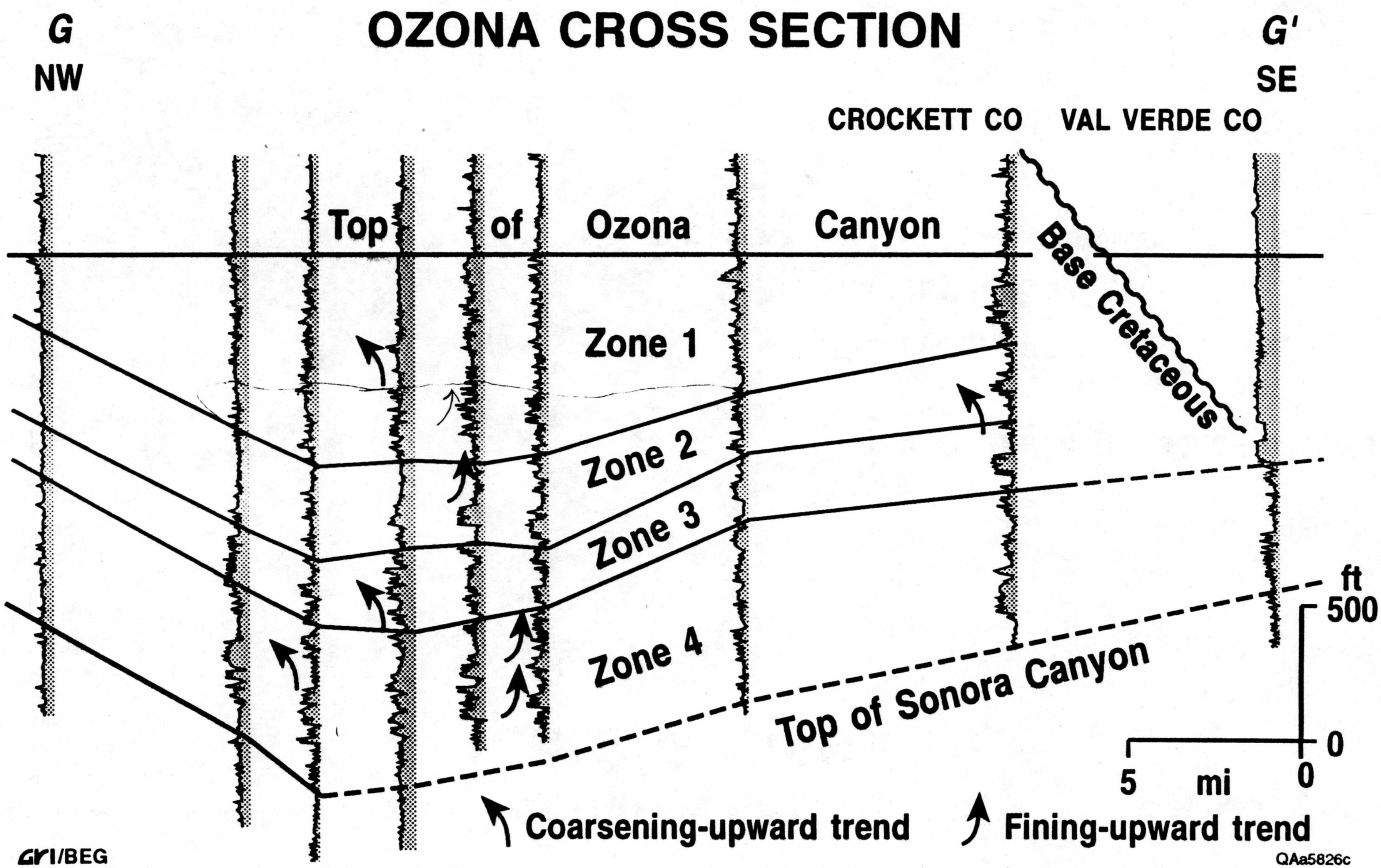
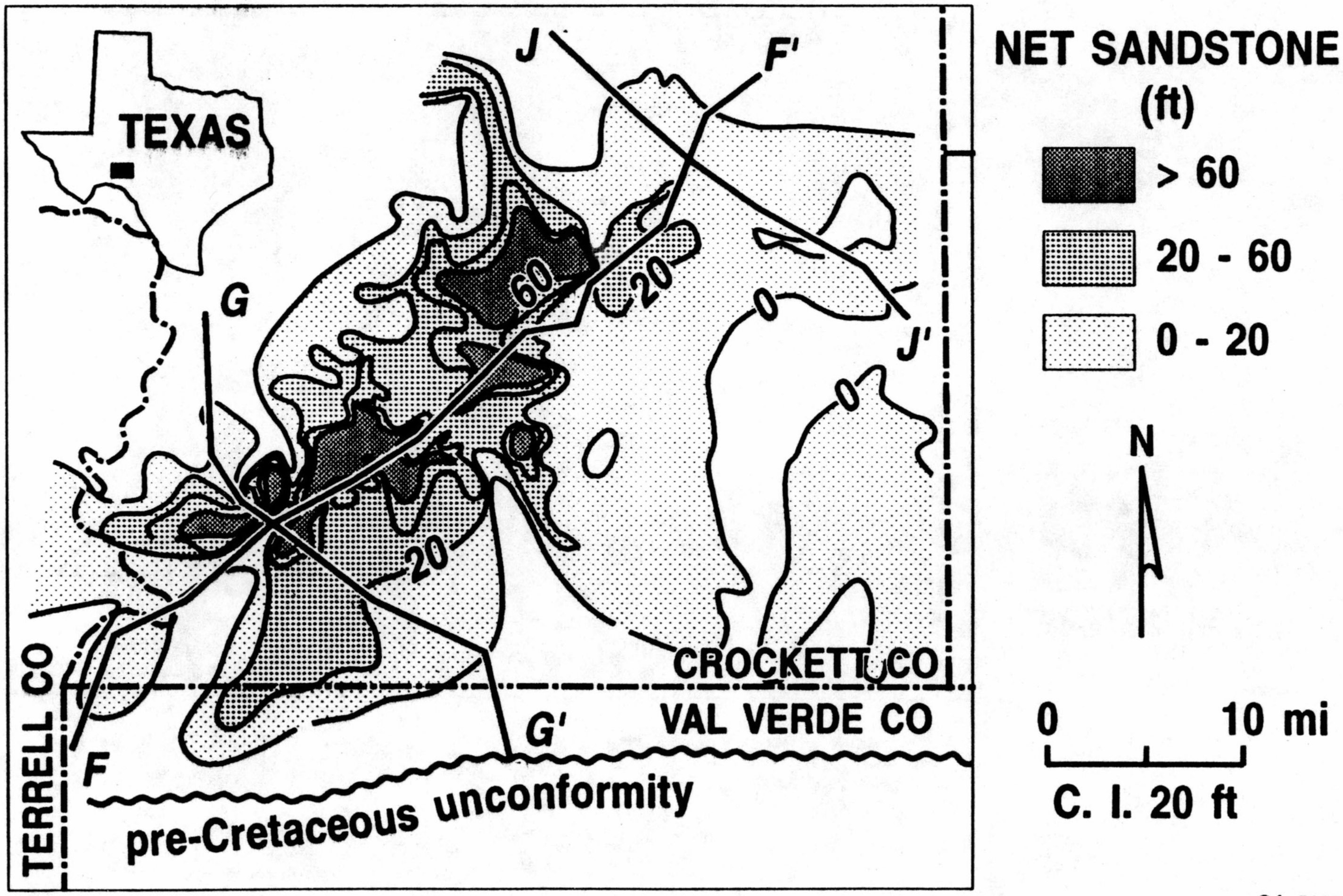
OZONA CROSS SECTION



OZONA ZONE 1
NET SANDSTONE



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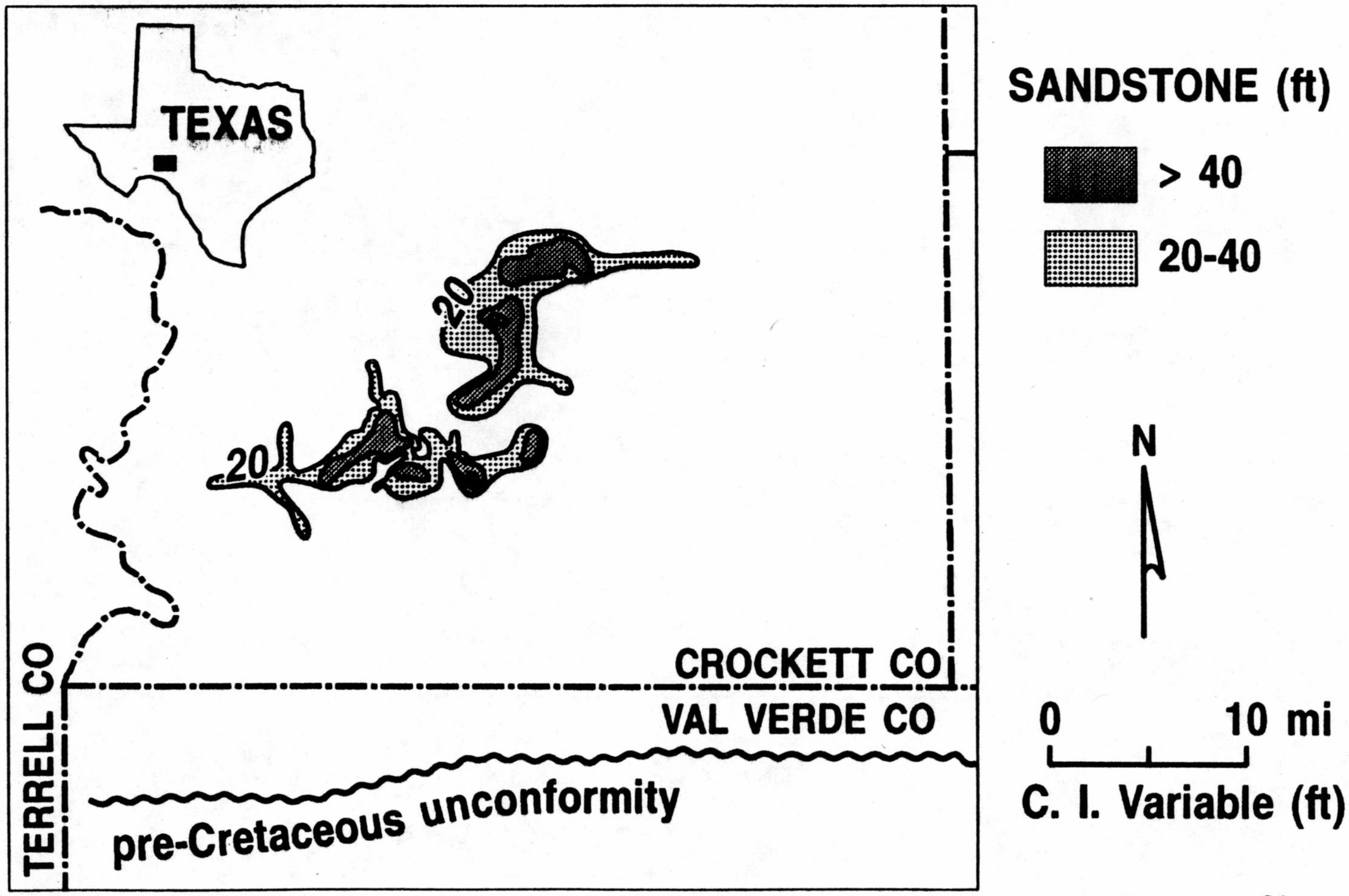
OZONA ZONE 1
MAXIMUM SANDSTONE



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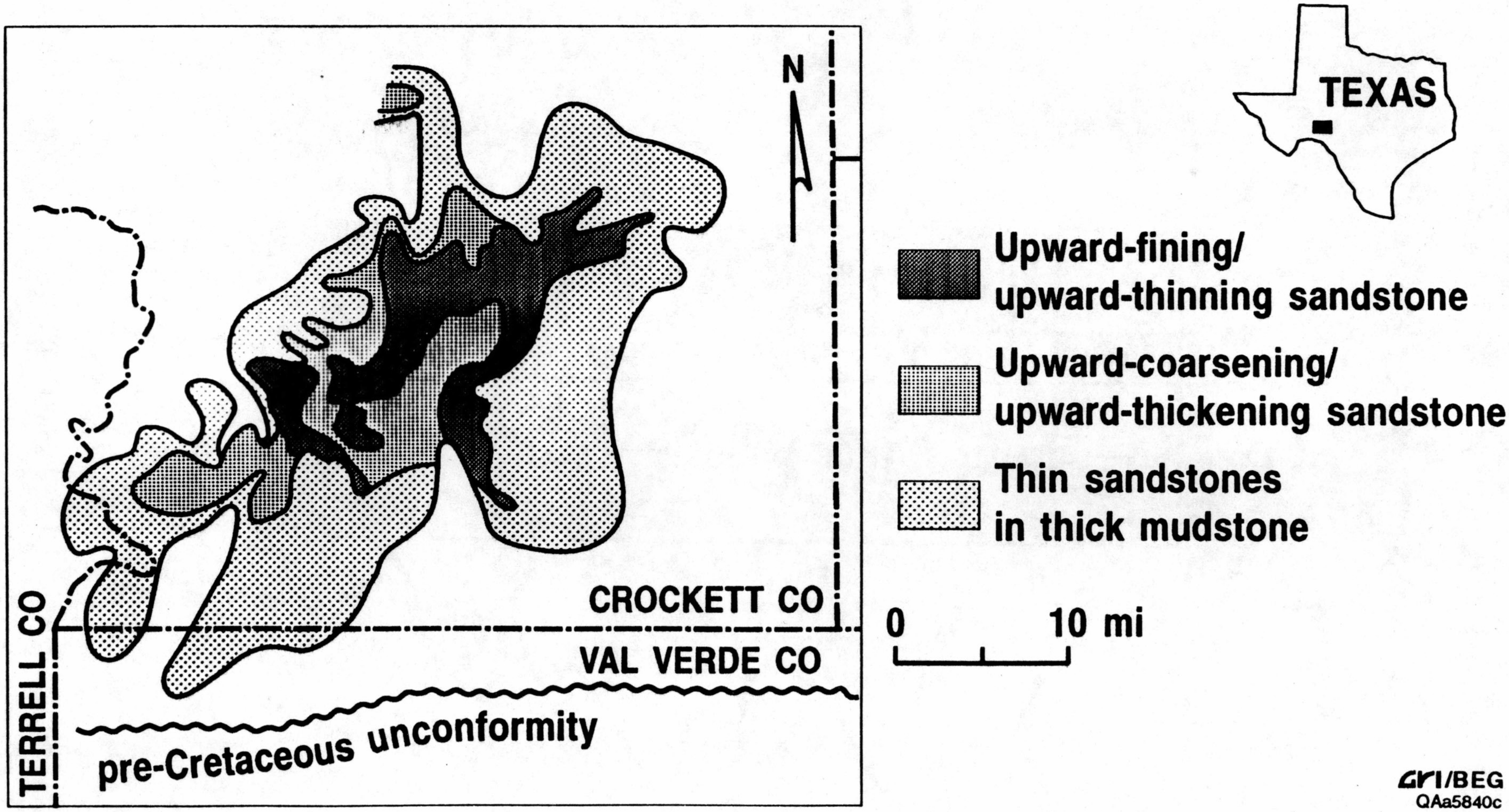
OZONA ZONE 1
LOG FACIES



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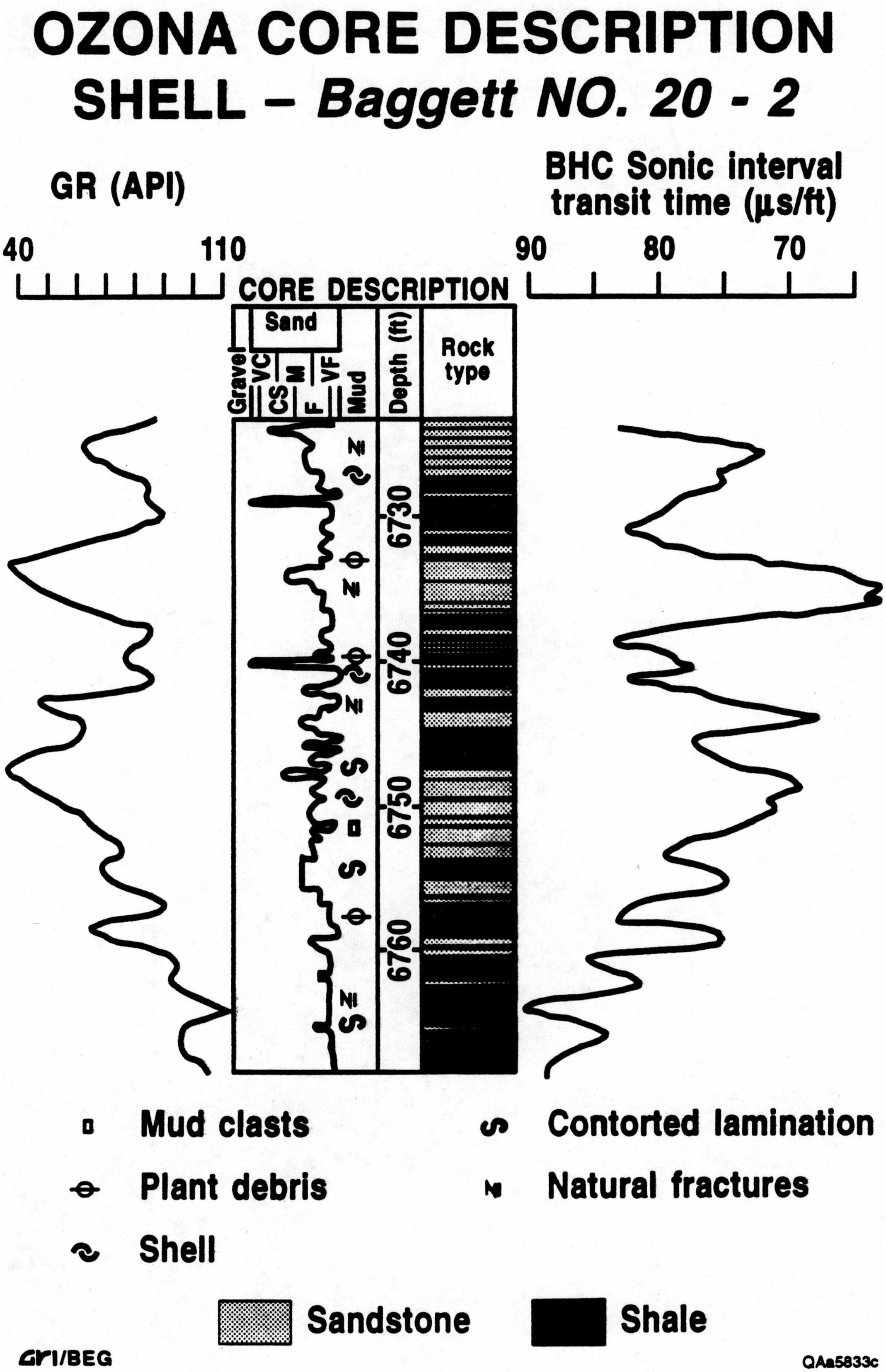

OZONA CORE DESCRIPTION
SHELL – Baggett NO. 20 - 2
GR (API)
BHC Sonic interval transit time (µs/ft)
40
110
90
80
70
CORE DESCRIPTION
Sand
Gravel
VC
CS
M
F
VF
Mud
Depth (ft)
Rock type
6730
6740
6750
6760
Mud clasts
Plant debris
Shell
Contorted lamination
Natural fractures
Sandstone
Shale
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QAa5833c

OZONA CANYON SUMMARY

- **Shale-Dominated Interval—Complex Sandstone Geometries**
- **Productivity Poorly Correlated with Regional Sandstone Distribution**
- **Maximum Sandstone and Log Facies Maps Help Identify Prospective Reservoirs**

OZONA CANYON SANDSTONE COMPOSITION AND DIAGENESIS

Presented by:

Tucker F. Hentz

Bureau of Economic Geology

The University of Texas at Austin

Austin, Texas

PURPOSE AND METHODS

- Sandstone Samples Examined for Texture, Composition, and Diagenesis

- 16 Samples from 2 Cores *(Texaco Kincaid No. D-7, Shell Baggett No. 2-20)*

- Standard Thin-Section Petrography and SEM Techniques

- 200 Point Counts per Thin Section

TEXTURE

- Very Fine to Coarse (Average: Fine Sandstone)
- Very Poor to Moderate Sorting
- Angular to Subrounded Grains
- Average Matrix Content 4.5%

COMPOSITION

- **Mean Composition of Framework Grains (Normalized to 100%): Q_{72} F_8 R_{20}**
- **Mineralogically Immature: Sublitharenites and Litharenites**

/BEG

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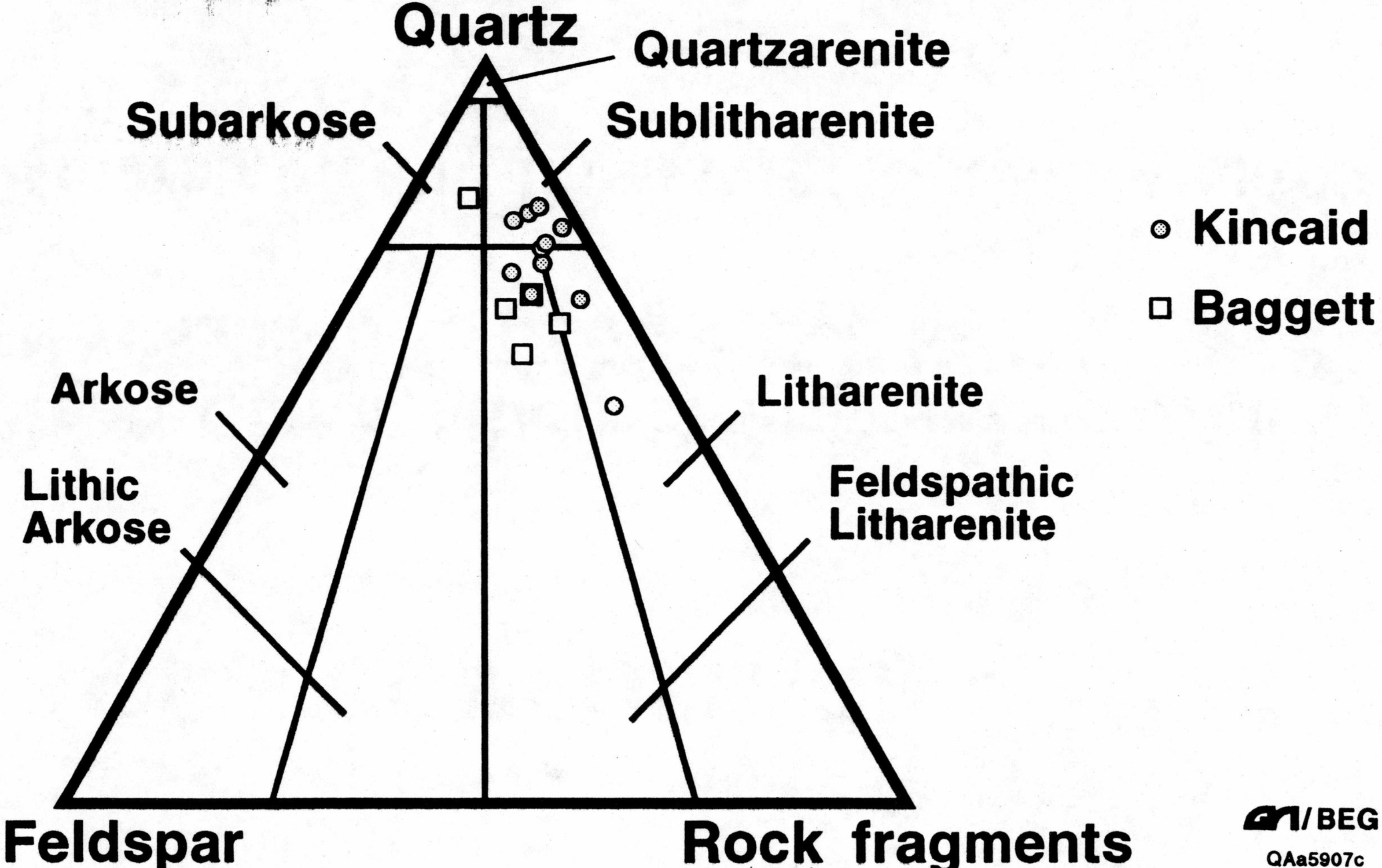
OZONA CANYON SANDSTONE COMPOSITION



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FRAMEWORK GRAINS

- Quartz: 26.0 to 54.5% of Whole-Rock Volume
- Plagioclase: 1.5 to 7.5% of Whole-Rock Volume
- Rock Fragments: 2.0 to 29.5% of Whole-Rock Volume
- Low-Rank MRF's Predominate: Phyllite, Slate, and Meta-Siltstone
- SRF's: Shale, Chert, and Limestone
- Mean Whole-Rock % of Framework Grains: Quartz (43.7), Plagioclase (4.3), Orthoclase (0.3), MRF's (8.2), SRF's (3.9)

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AUTHIGENIC CEMENTS

- Ankerite, Quartz, Chlorite, and Fe-Calcite (18.4, 6.4, 3.7, and 3.2 Mean Whole-Rock %)

- Replacive Minerals (Mostly Pyrite and Ilmenite) Occur in Trace Amounts

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DIAGENETIC SEQUENCE

(1) Growth of Chlorite Rims on Framework Grains

(2) Compaction, Causing Deformation of Ductile Rock Fragments

(3) Precipitation of Quartz Overgrowths

(4) Precipitation of Ankerite and Fe-Calcite, Dissolution of Feldspar and MRF's

(5) Pressure Solution and Additional Silica Cementation at Quartz-to-Quartz Contacts

(6) Fracturing

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POROSITY

- Thin-Section Porosity (Primary, Secondary) Varies From 0 to 6.5% of Whole-Rock Volume (Mean = 1.4%)
- Primary Porosity Exists as Small (Several Microns) Intergranular Voids and Within Cements
- Secondary Porosity Occurs Within Partially Dissolved Feldspars, MRF's, and Shale Clasts
- Mean Net-Overburden Porosimeter Porosity is 7.6%
- Microporosity Occurs as Voids Between Chlorite Platelets and Within Ankerite and Calcite Cements

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POROSITY LOSS

- Ductile, Compaction-Deformed MRF's
- Pore-Filling Cements, Primarily Ankerite, Quartz, and Fe-Calcite
- Cements (Ankerite, Fe-Calcite) Replacing Partially and Wholly Dissolved Framework Grains (Feldspar, Pelitic MRF's and SRF's)

PERMEABILITY

- **Mean Klinkenberg-Corrected Gas Permeability at Net-Overburden Pressure is 0.024 Md**

- **Presence of Microfractures in 25% of Thin Sections Correlates with Samples of Slightly Higher Permeabilities**

SUMMARY

- Quartz and Pelitic Rock Fragments are the Most Abundant Framework Grains
- Ankerite and Fe-Calcite are the Primary Cements
- Voids Within Carbonate Cements, Partially Dissolved Framework Grains, and Microfractures Compose Visible Porosity
- Microporosity is Present Within Chlorite Grain-Rimming Cement and Carbonate Cements
- Porosity is Occluded by Extensive Late-Stage Carbonate Cementation and by Compaction Deformation of Ductile Rock Fragments

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SUMMARY OF OZONA CANYON FRACTURES

Presented by:

Stephen E. Laubach

Bureau of Economic Geology

The University of Texas at Austin

Austin, Texas

NATURAL FRACTURES

Abundant

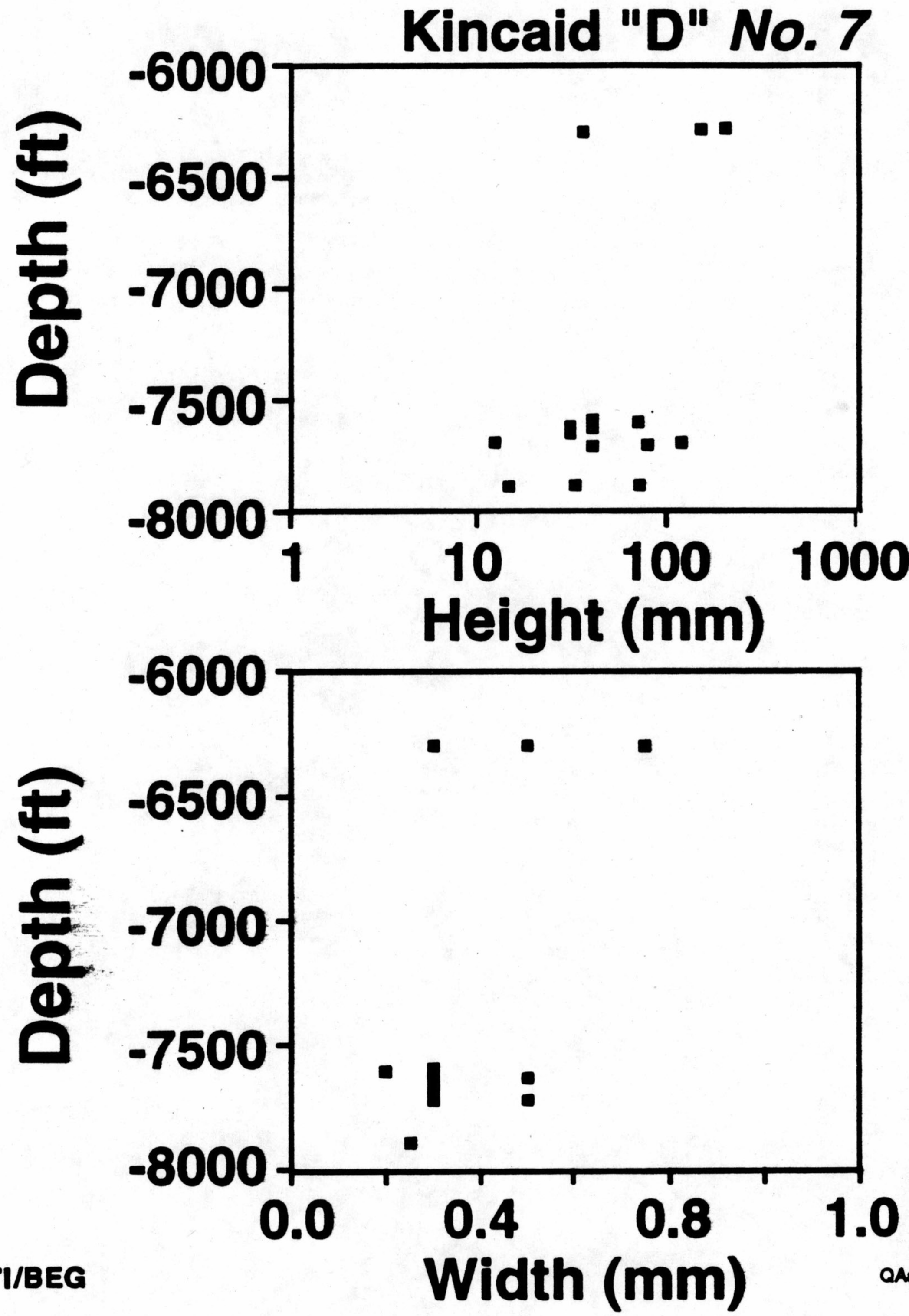
Vertical

Locally Porous

Mainly Short (>10 inches)

Several Categories (classes)

OZONA FRACTURE HEIGHT/WIDTH VS. DEPTH



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STRATIGRAPHY AND PRODUCTIVITY OF SONORA CANYON SANDSTONE, SUTTON COUNTY

Presented by:

H. Scott Hamlin

Bureau of Economic Geology

The University of Texas at Austin

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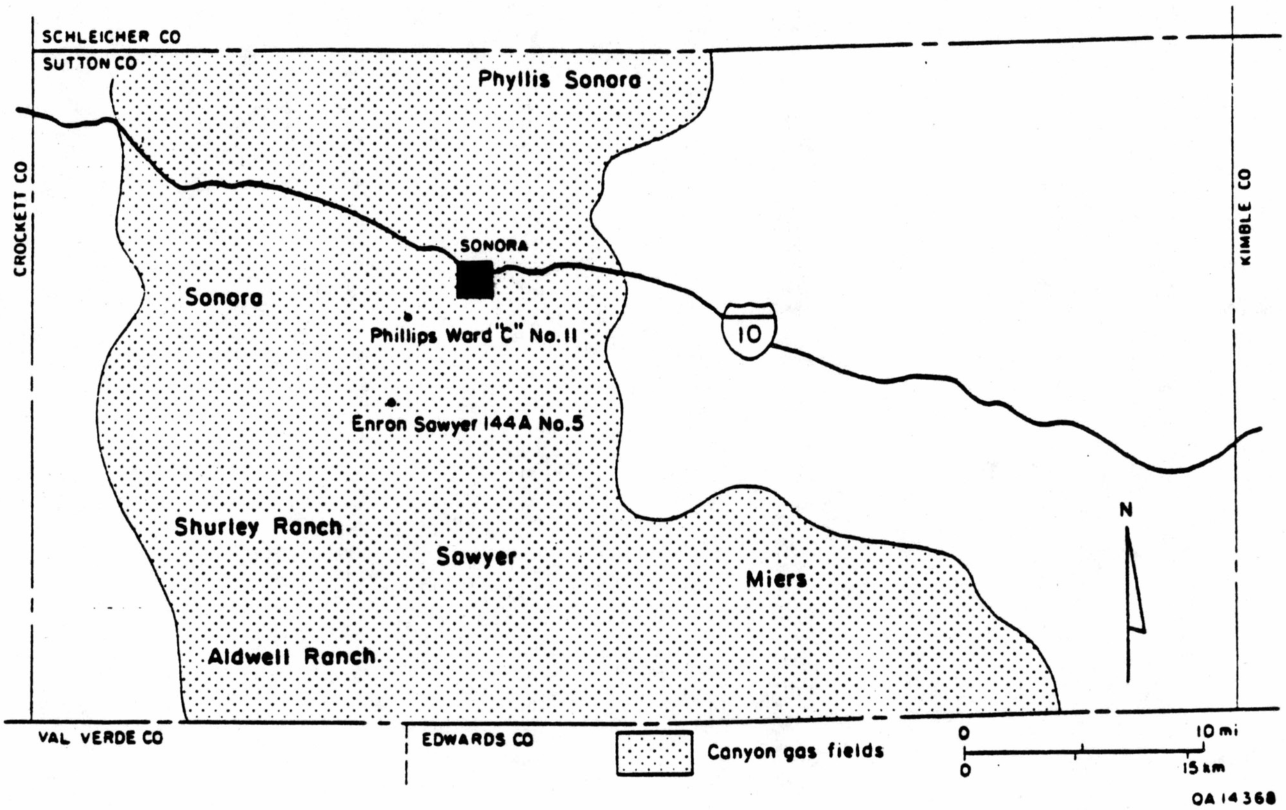
SONORA CANYON STRATIGRAPHY

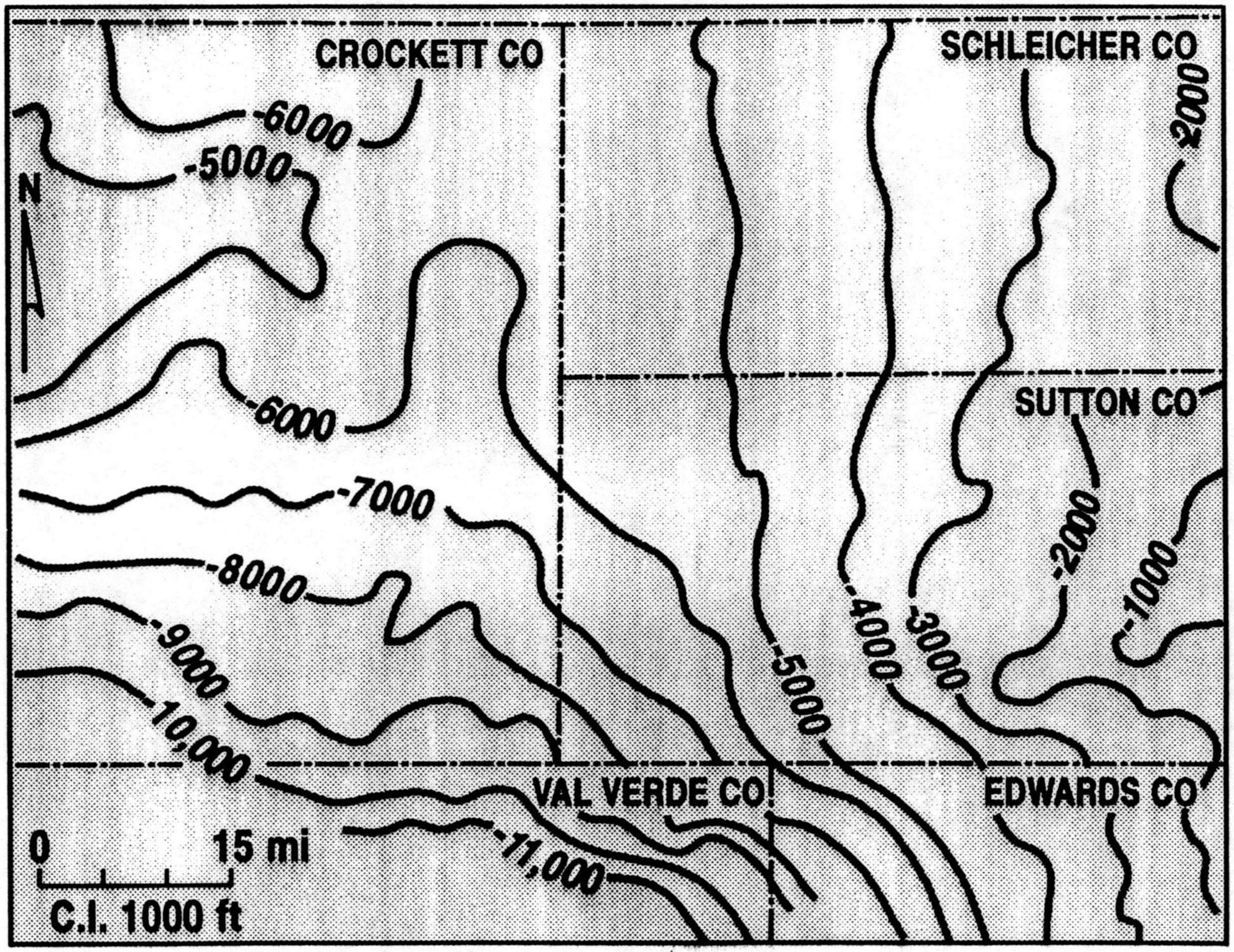
- Laterally Discontinuous Submarine-Fan Sandstones

- Highly Laminated Turbidite Sequences

- Facies Influence Production Patterns

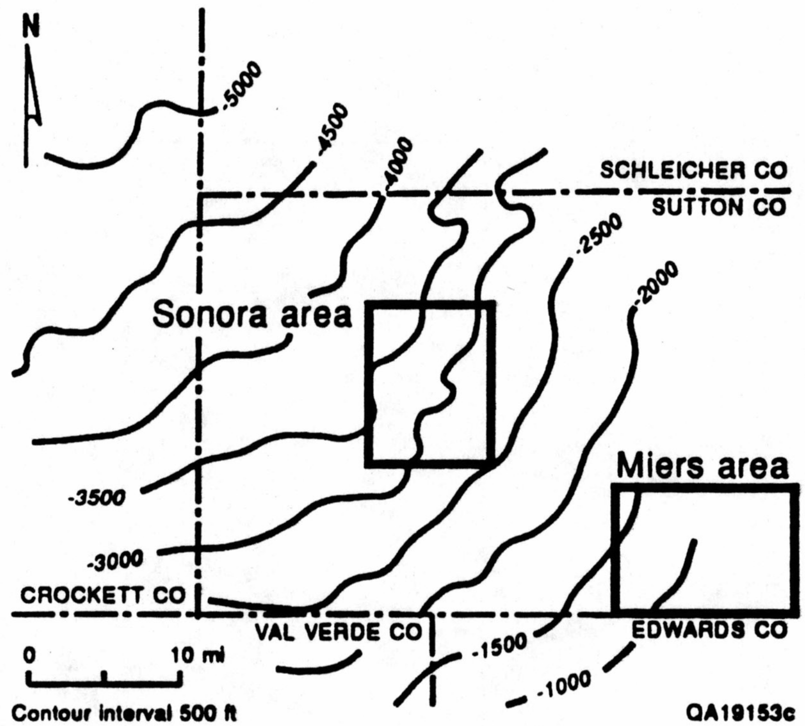

SCHLEICHER CO
SUTTON CO
Phyllis Sonora
CROCKETT CO
KIMBLE CO
SONORA
Sonora
10
Phillips Ward "C" No. 11
Enron Sawyer 144A No. 5
N
Shurley Ranch
Sawyer
Miers
Aldwell Ranch
VAL VERDE CO
EDWARDS CO
Canyon gas fields
0
10 mi
0
15 km
QA 14368

STRUCTURE MAP
TOP OF PENNSYLVANIAN LIMESTONE



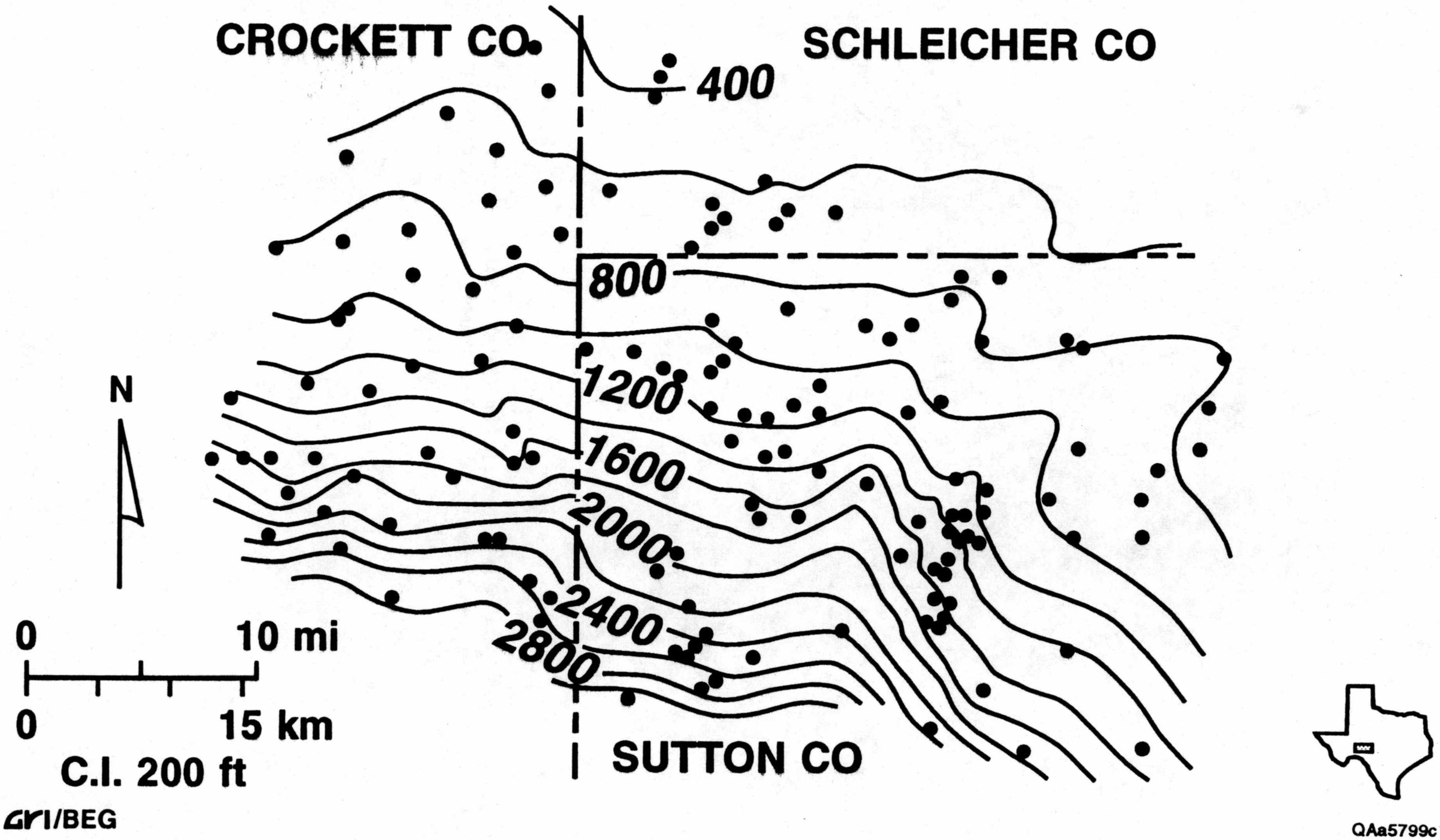
Bureau of Economic Geology

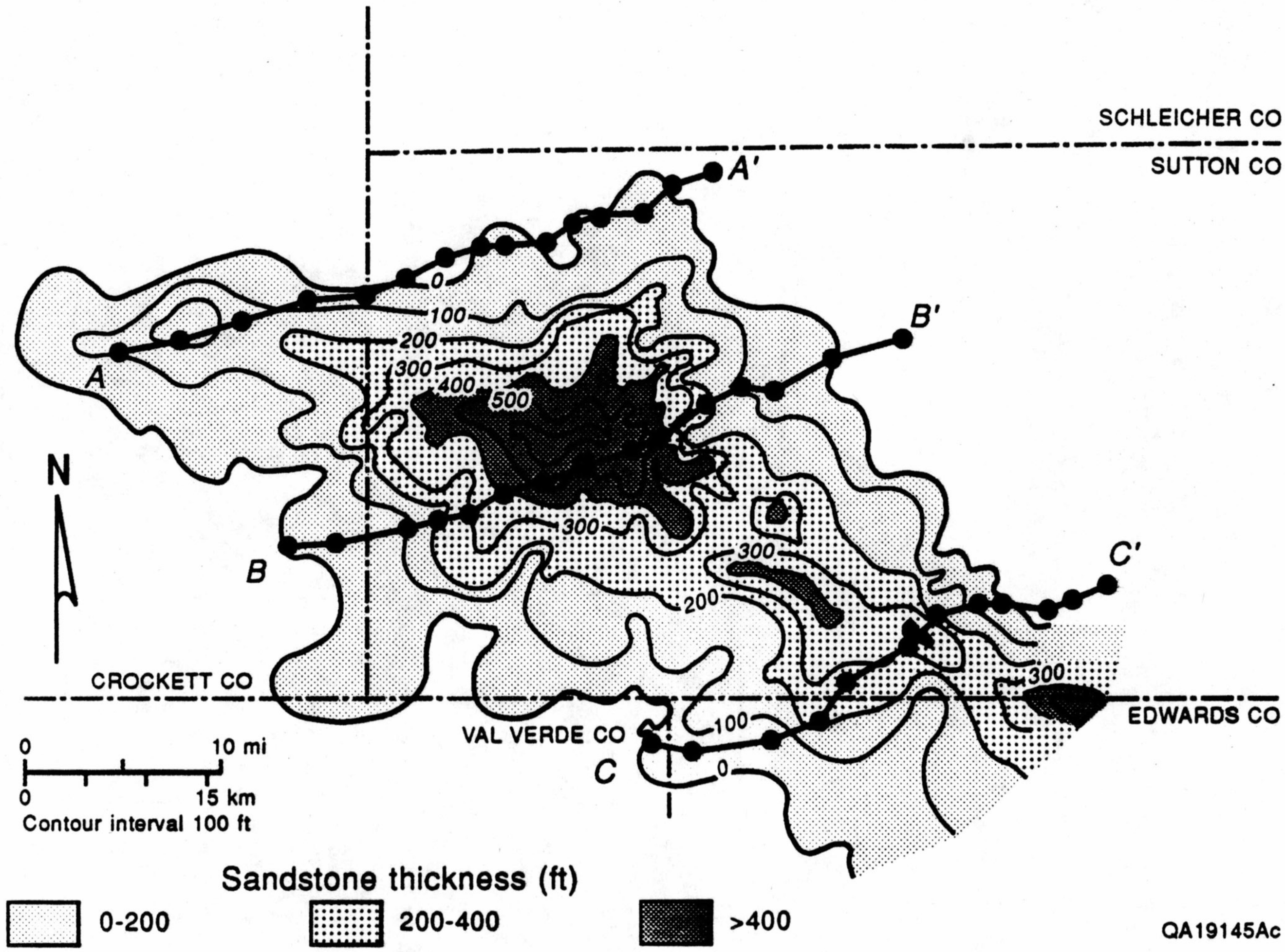
QA19146c



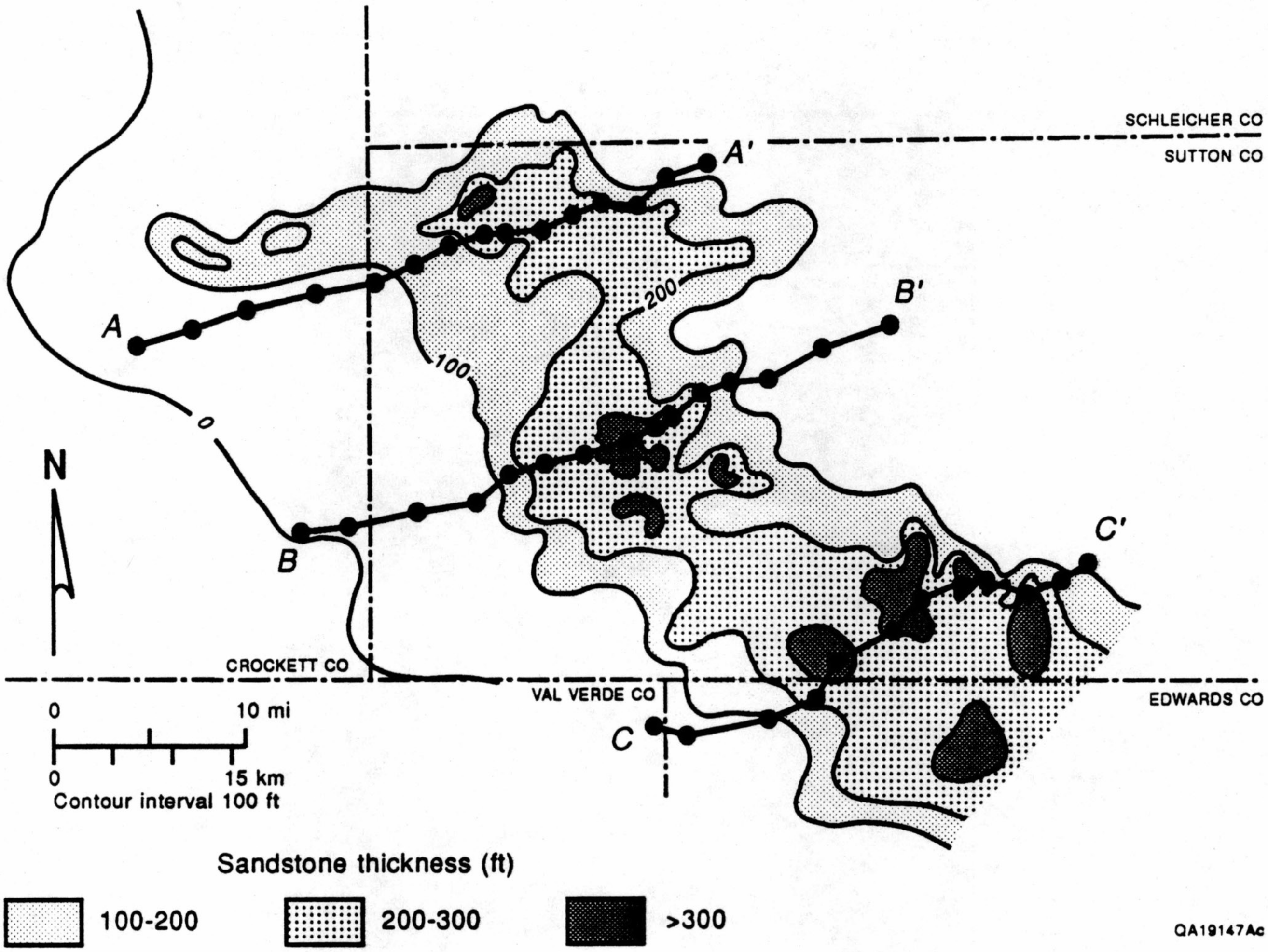
Structure map contoured on the Sonora Canyon relative to a sea-level datum. Depths from land surface to Canyon sandstones range from about 3,000 to 7,000 feet in Sutton County. The areas of field-scale studies are outlined.

SONORA CANYON ISOPACH



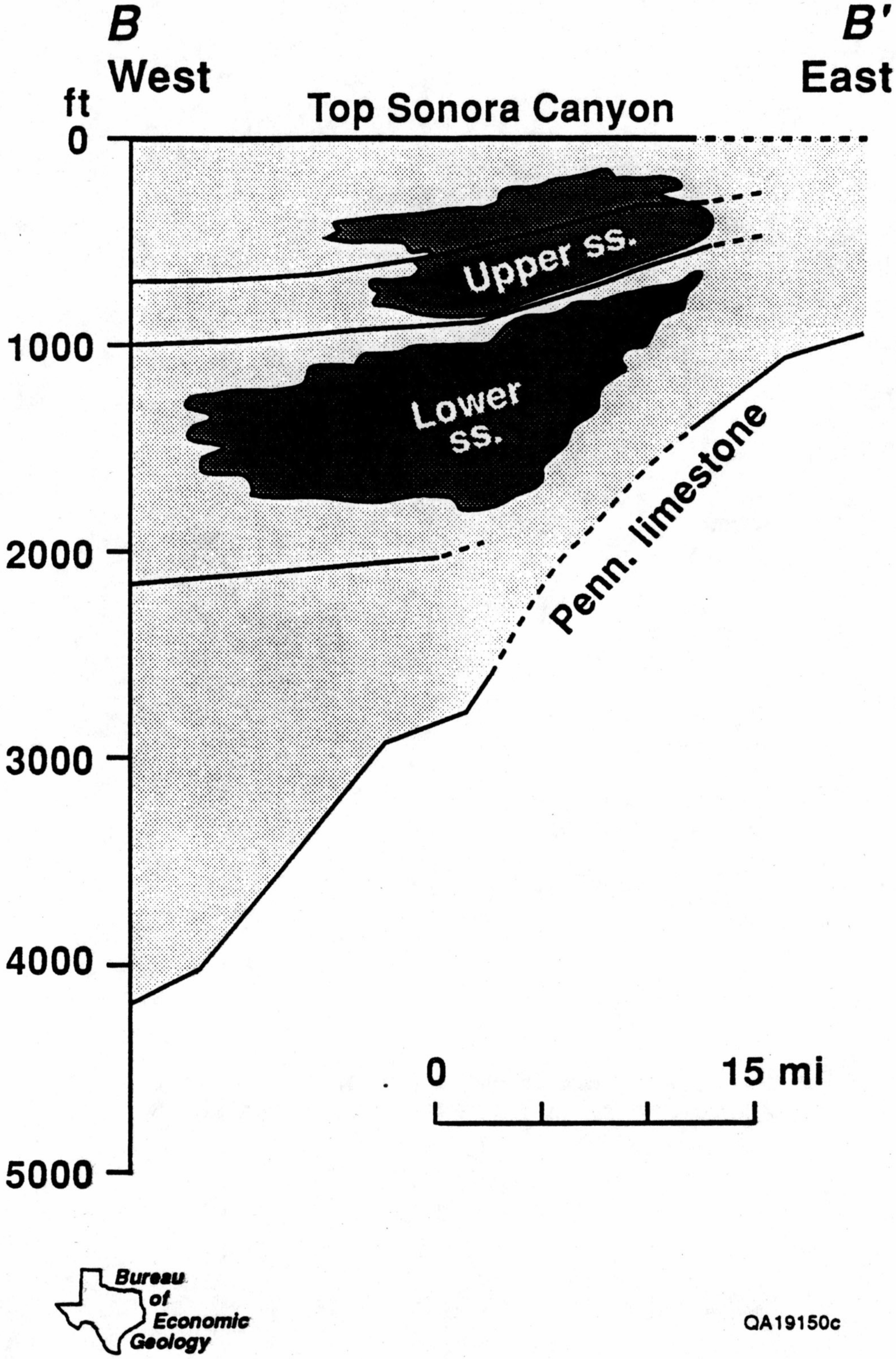


Net-sandstone thickness map of the lower Sonora Canyon map unit, which includes both the lower and middle completion units (see Phillips well logs). The thickest sandstone is centered in the Sonora and Sawyer fields.

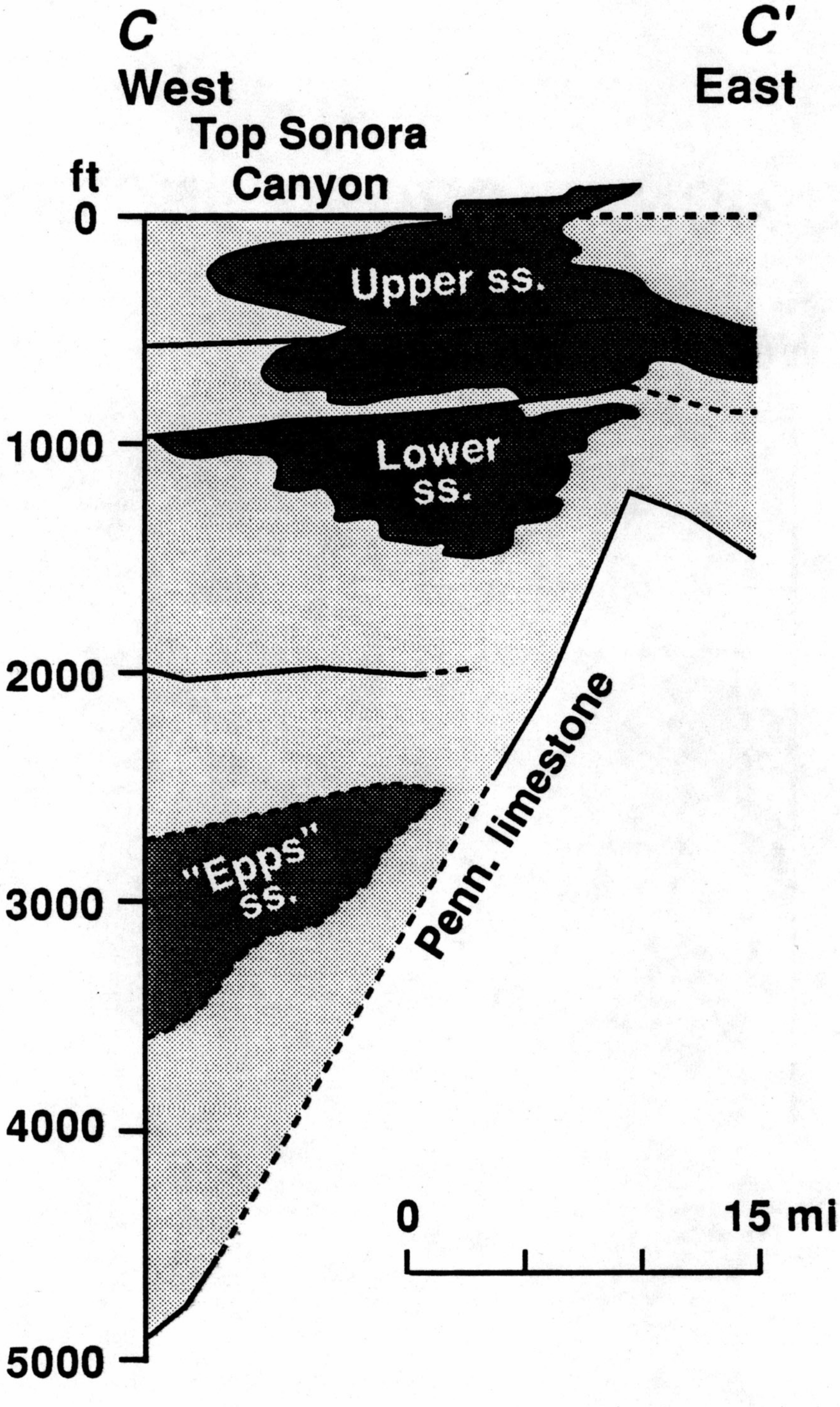


Net-sandstone thickness map of the upper Sonora Canyon map unit. The Sonora area cooperative wells lie in the thick sandstone about half way along cross section B-B' (illustrated next).

REGIONAL CROSS SECTION



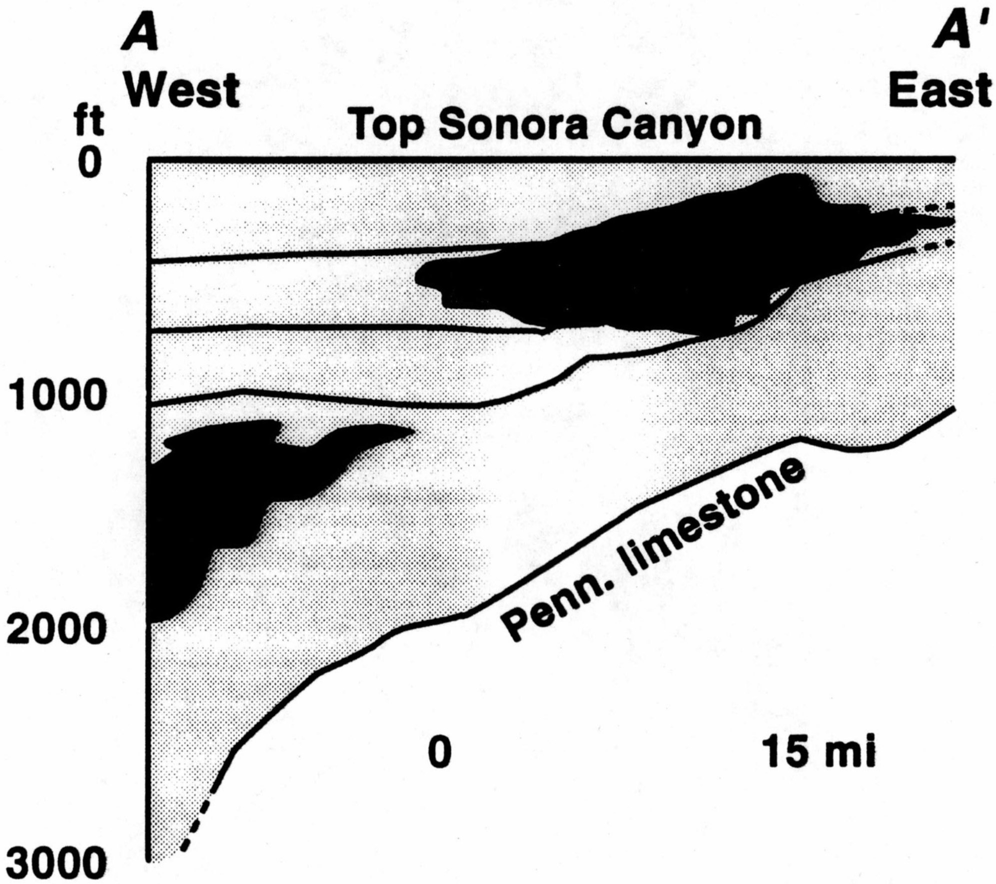
REGIONAL CROSS SECTION



Bureau of Economic Geology

QA19151c

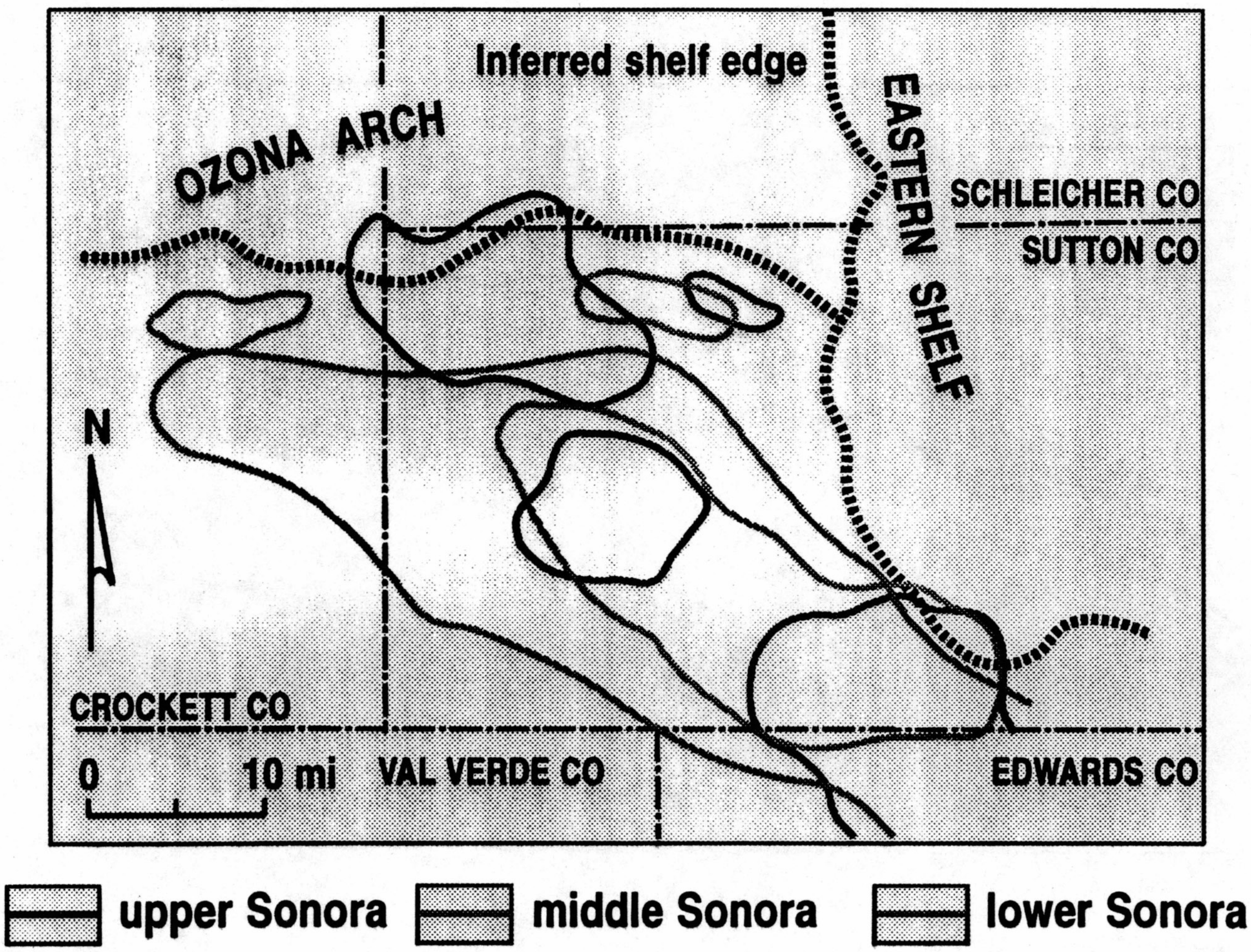
REGIONAL CROSS SECTION



Bureau of Economic Geology

QA19149c

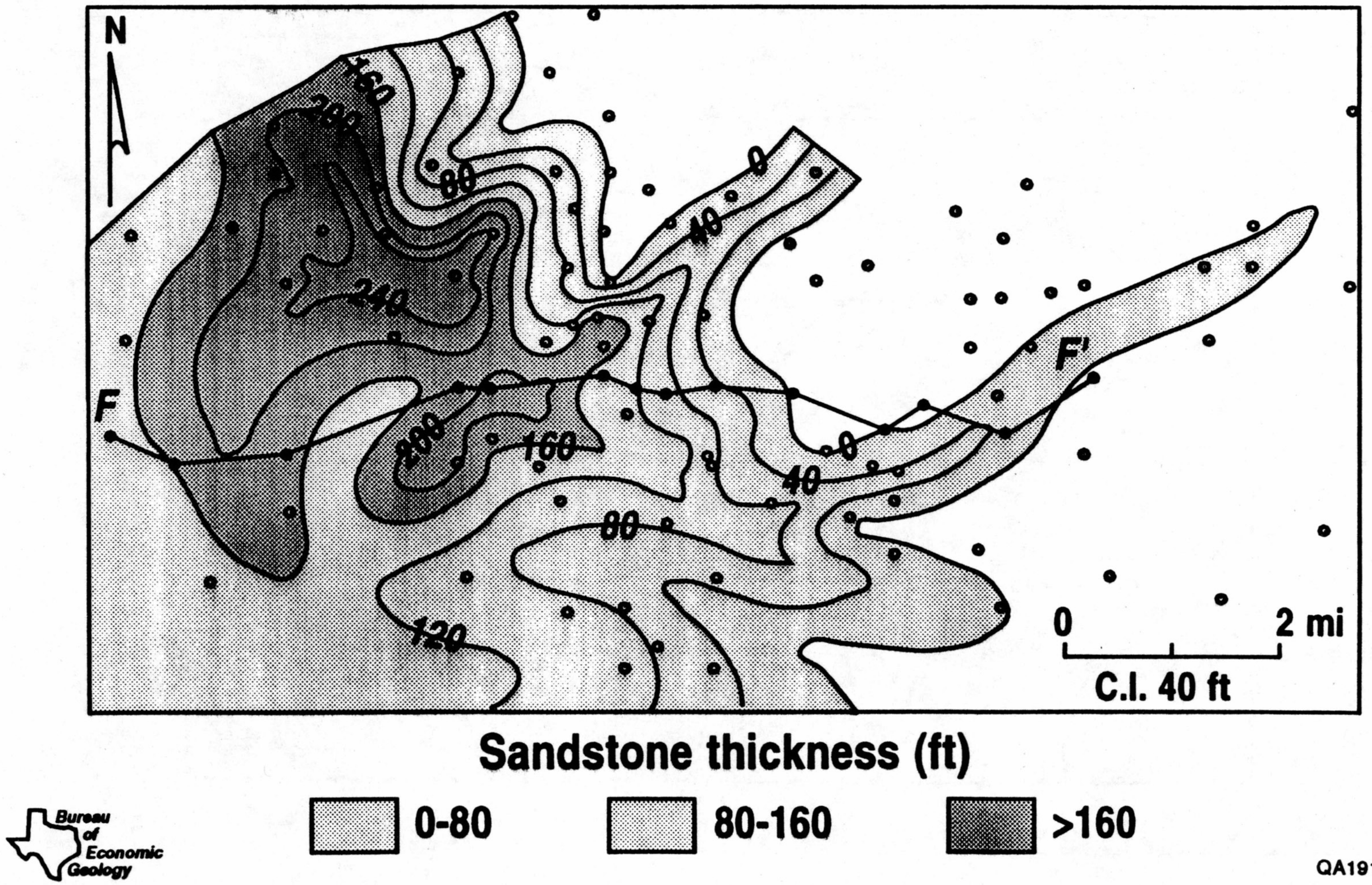
SONORA CANYON SANDSTONE DEPOCENTERS



Bureau of Economic Geology

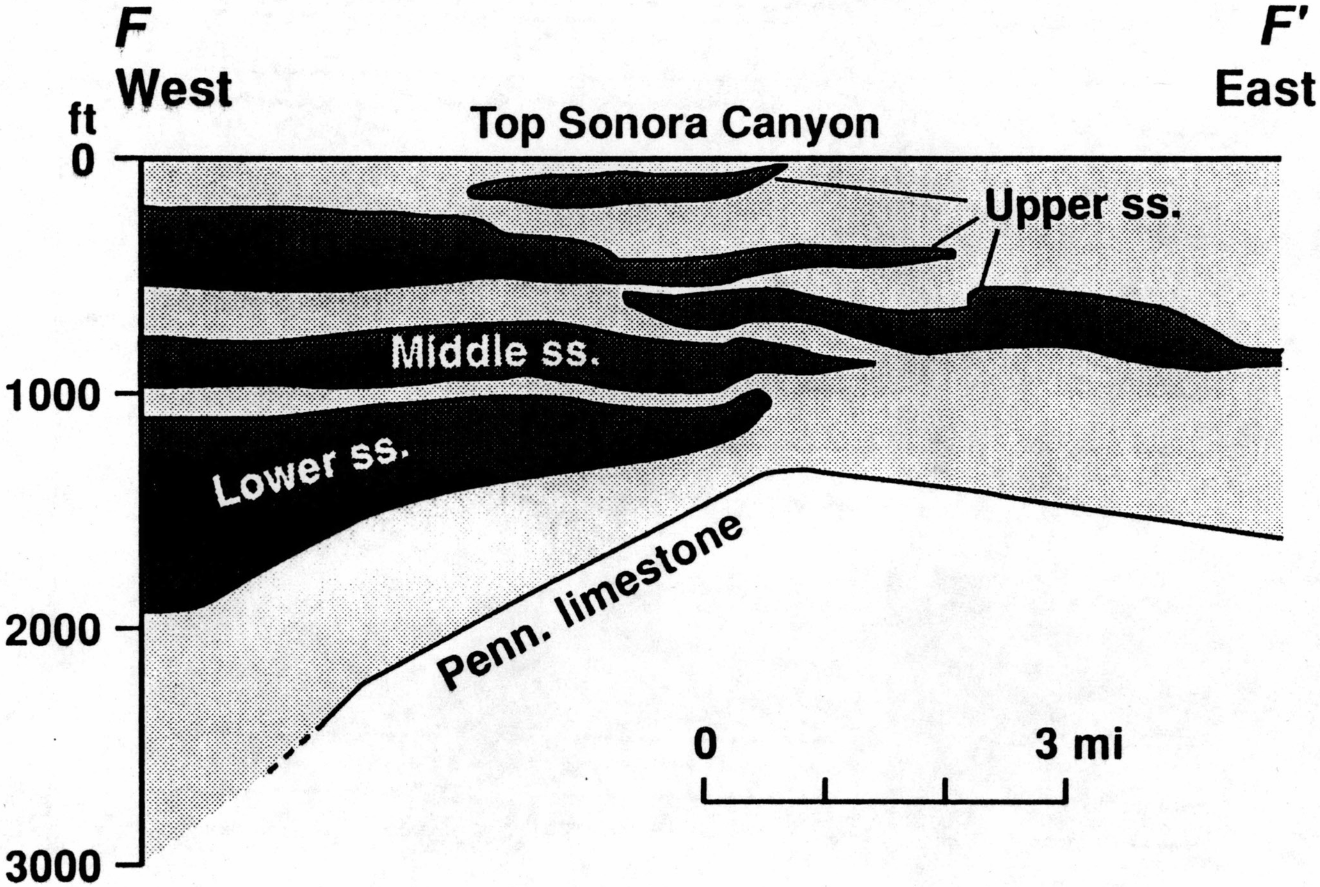
QA19144c

MIDDLE SONORA CANYON NET SANDSTONE
MIERS AREA



QA19148c

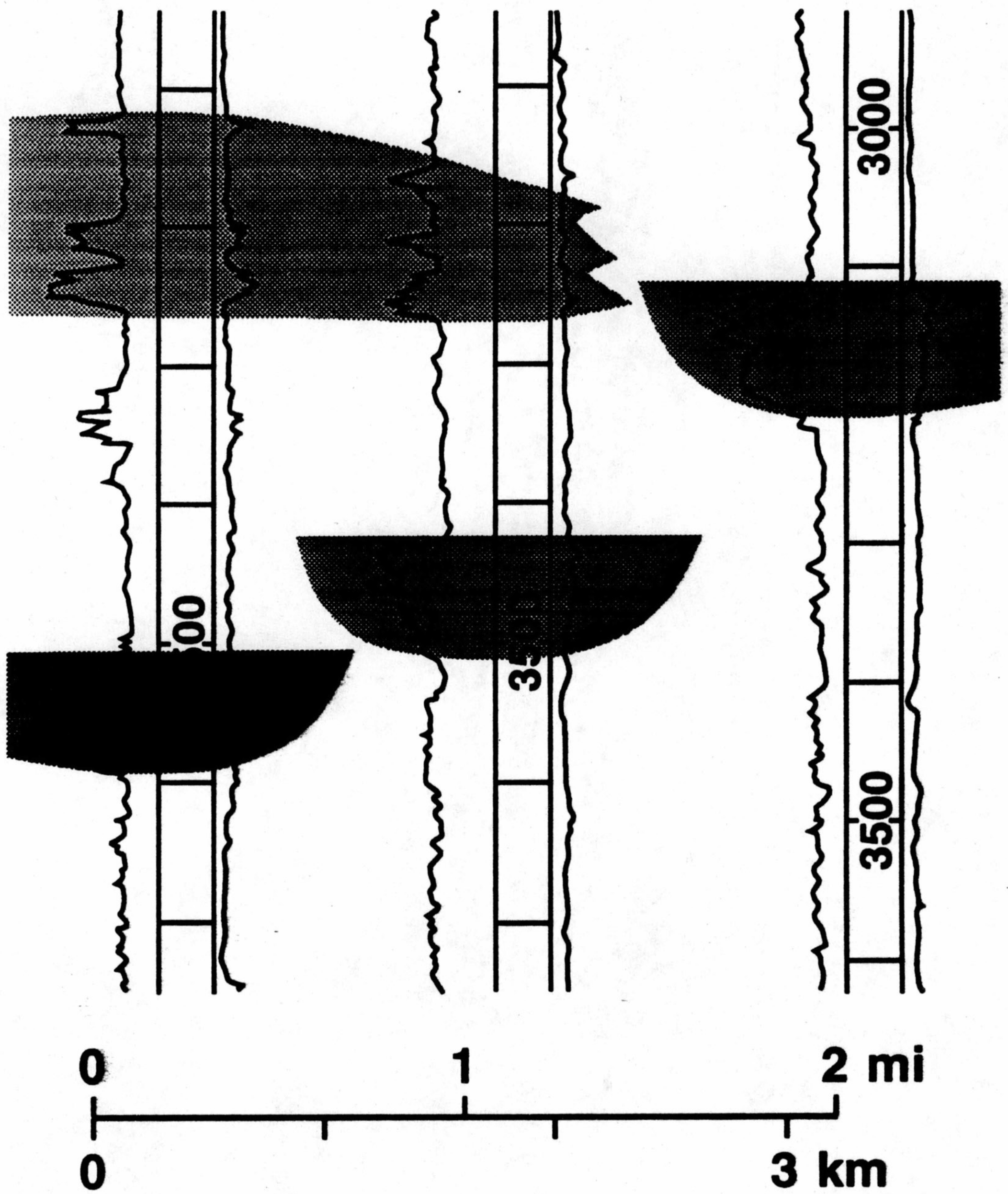
MIERS AREA CROSS SECTION



Bureau of Economic Geology

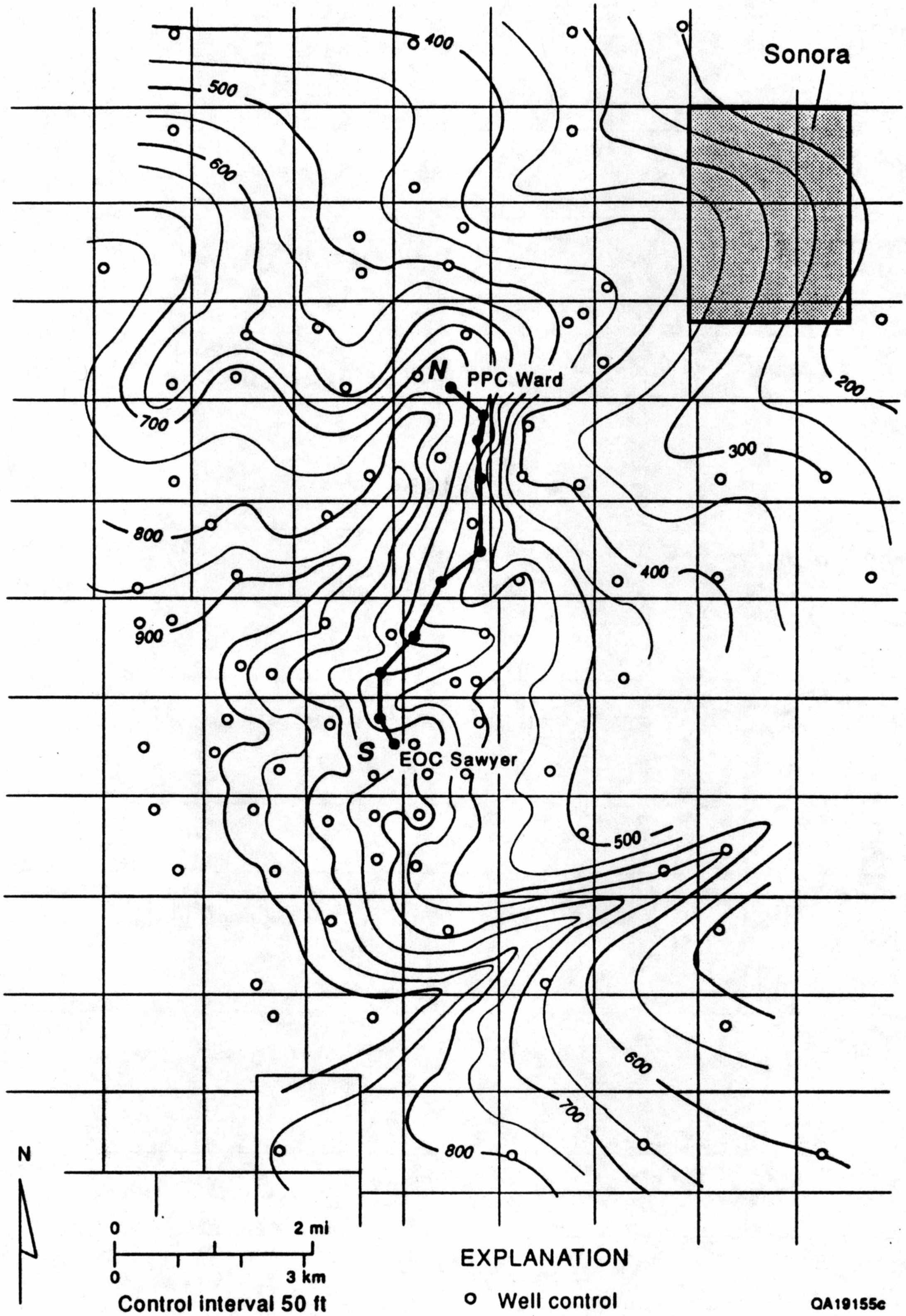
QA19152c

SLOPE CHANNELS
MIERS FIELD

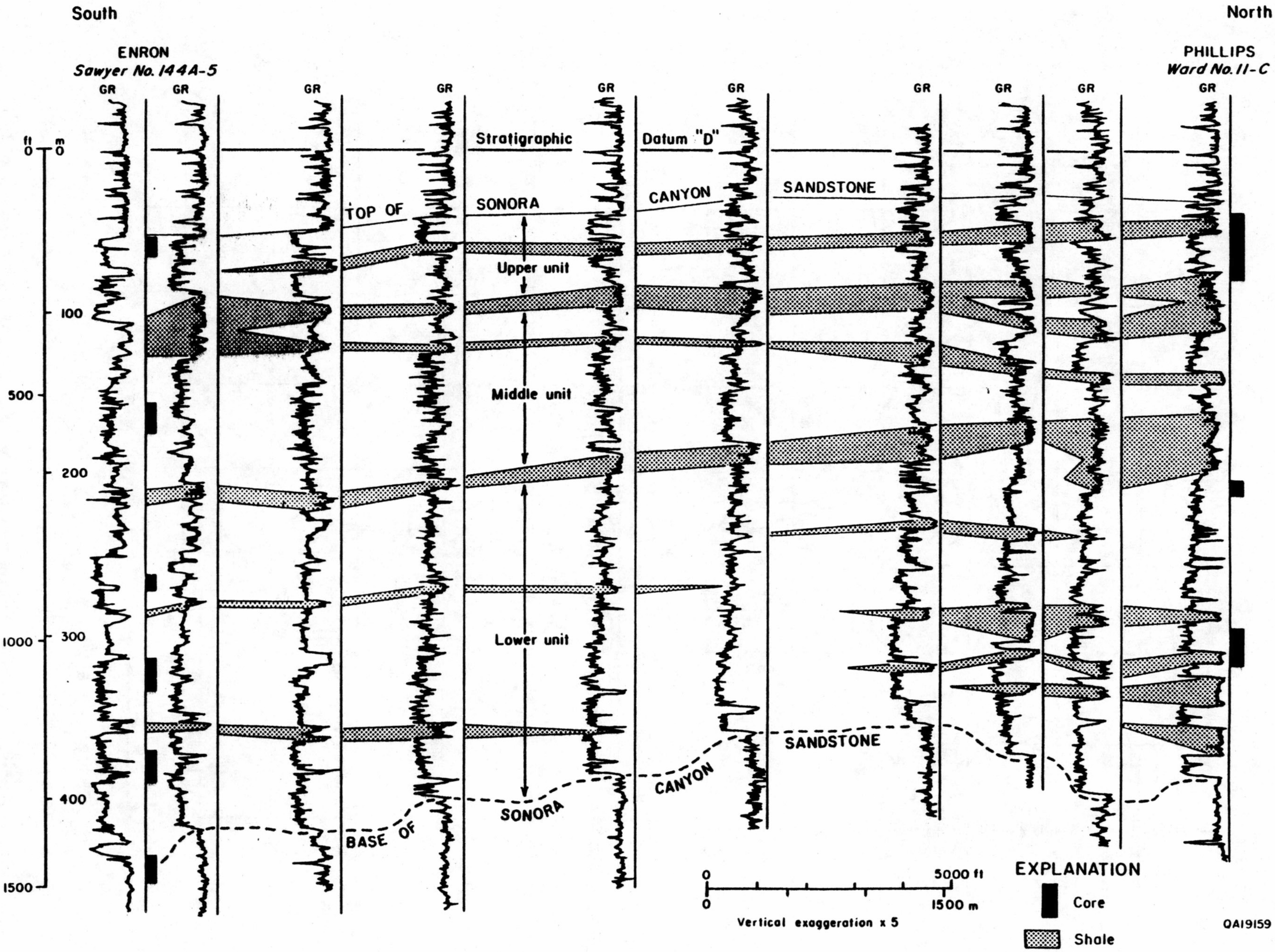


GRI/BEG

QAa5801c

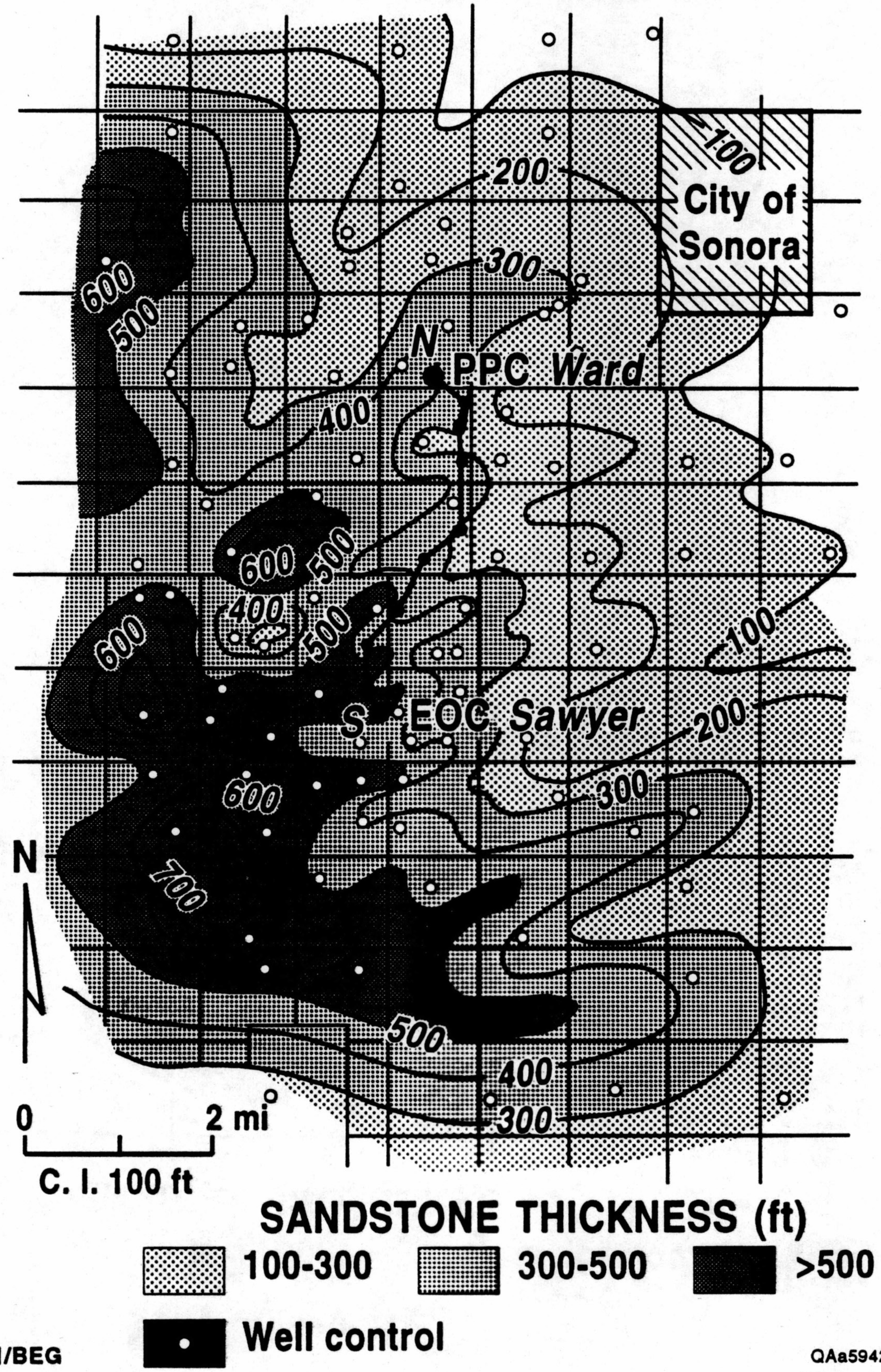


Gross thickness of the lower Sonora Canyon map unit in the area around the cooperative wells. Narrow northeast-trending zones of maximum thickness represent infilling of submarine canyons that were eroded into underlying slope shales.



South
North
ENRON
Sawyer No. 144A-5
PHILLIPS
Ward No. 11-C
GR
Stratigraphic
Datum "D"
TOP OF
SONORA
CANYON
SANDSTONE
Upper unit
Middle unit
Lower unit
BASE OF
SONORA
CANYON
SANDSTONE
ft
m
0
100
500
200
1000
300
400
1500
0
5000 ft
0
1500 m
Vertical exaggeration x 5
EXPLANATION
Core
Shale
QA19159

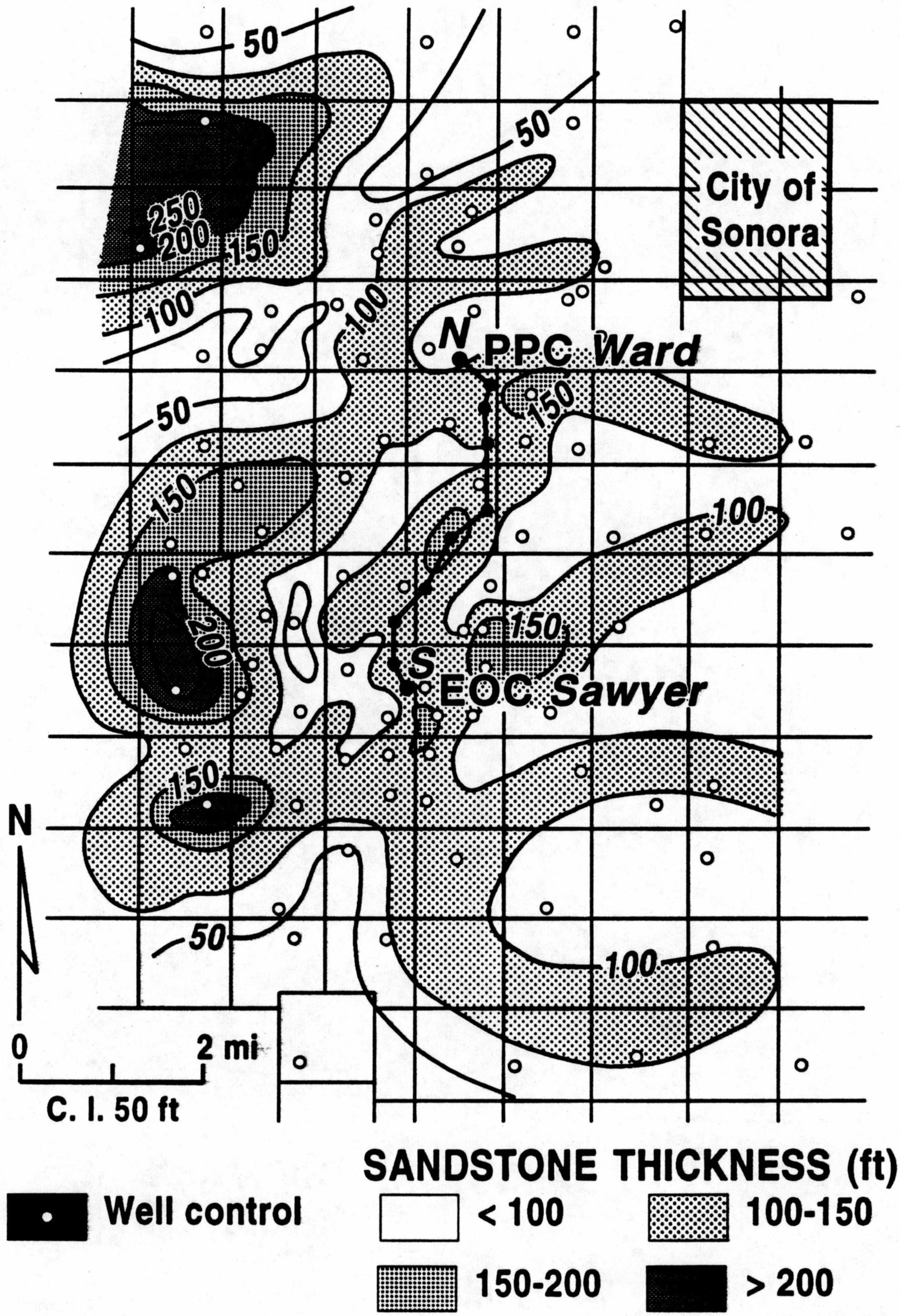
LOWER SONORA CANYON
NET SANDSTONE



GRI/BEG

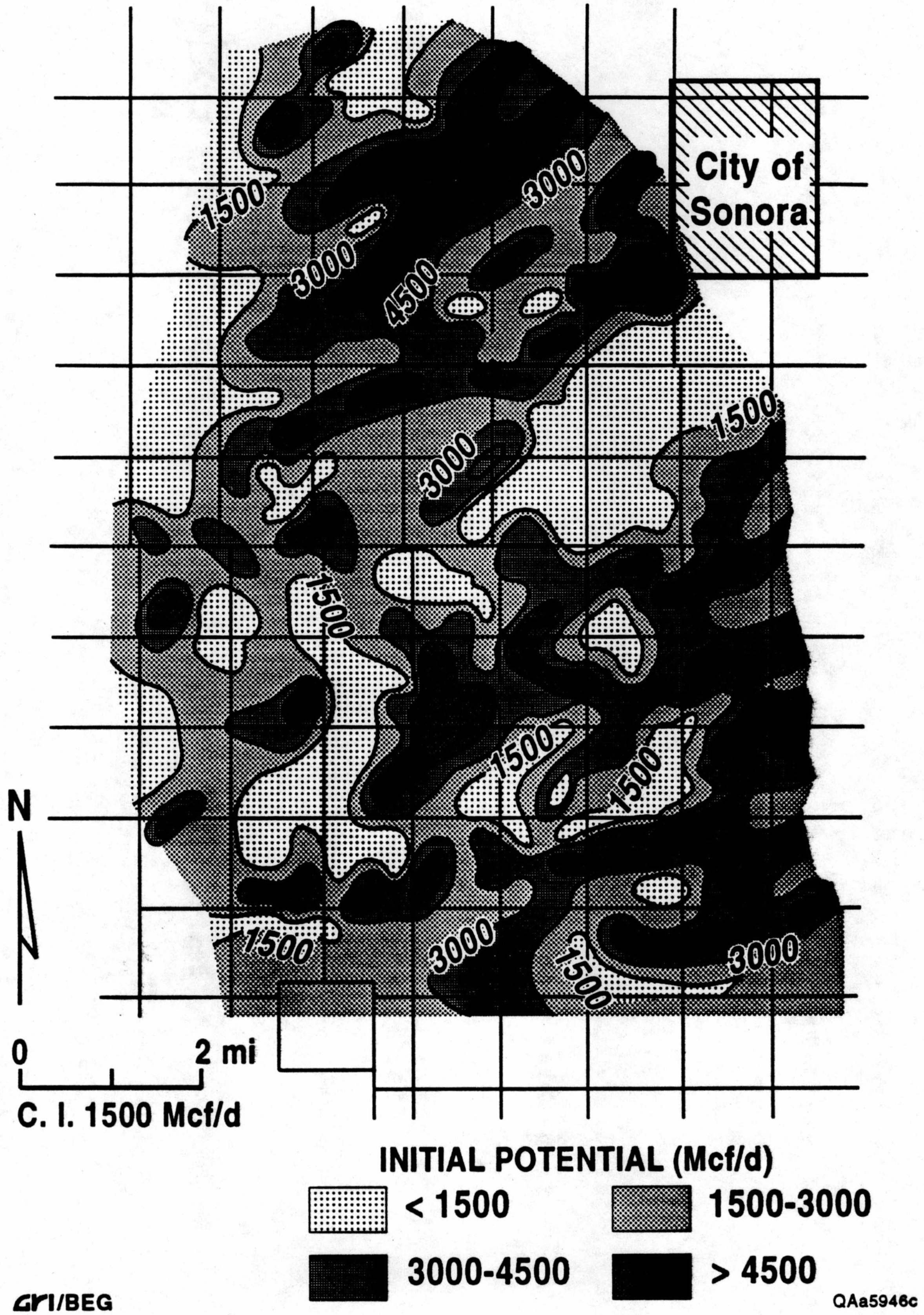
QAa5942c

LOWER SONORA CANYON MAXIMUM SANDSTONE



GRI/BEG QAa5944c

SONORA CANYON
INITIAL POTENTIAL



SONORA STRATIGRAPHY KEY FINDINGS

- **Widespread Thick Sandstone—Extreme Internal Heterogeneity**

- **Individual Sandstones Rarely more than a Few Feet Thick**

- **Highly Lenticular Fan-Channel Sandstones Less than 1 Mile Wide**

- **More Sheetlike Fan-Lobe Sandstones Extend only a Few Miles**

- **Facies-Influenced Production Patterns Modified by Post-Depositional Process**

DIAGENESIS AND RESERVOIR QUALITY OF SONORA CANYON SANDSTONE

Presented by:

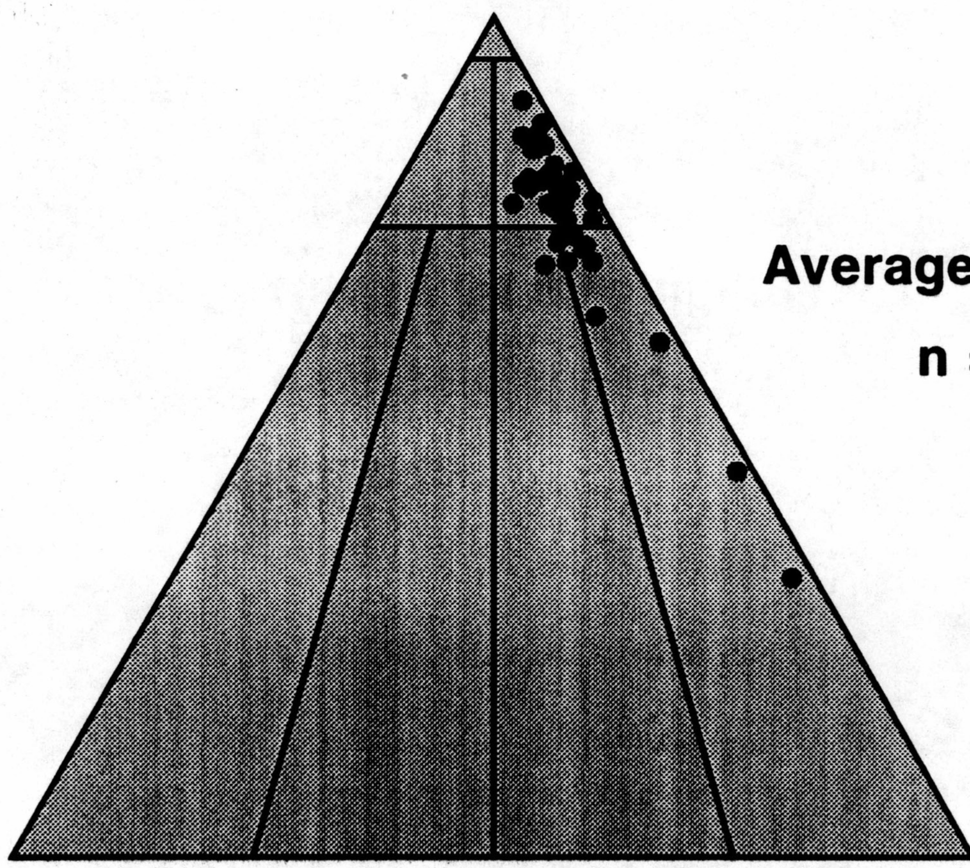
Shirley P. Dutton

Bureau of Economic Geology

The University of Texas at Austin

Austin, Texas

CANYON SANDSTONE COMPOSITION



Average $Q_{77}F_4R_{19}$

n = 44

GRI/BEG

QAa1715c

CANYON SANDSTONE
PARAGENETIC SEQUENCE

1. Siderite rims, chlorite
2. Quartz overgrowths
3. Calcite
4. Feldspar dissolution
5. Kaolinite and illite
6. Ankerite

GRI/BEG

QAa2310c

SIDERITE OCCURRENCE

- Bedding-parallel layers
  - Mean thickness (geometric) = 2 inches
  - Most layers <3 inches thick
- Irregular patches <3 – 4 inches in diameter

GRI/BEG QAa2313c

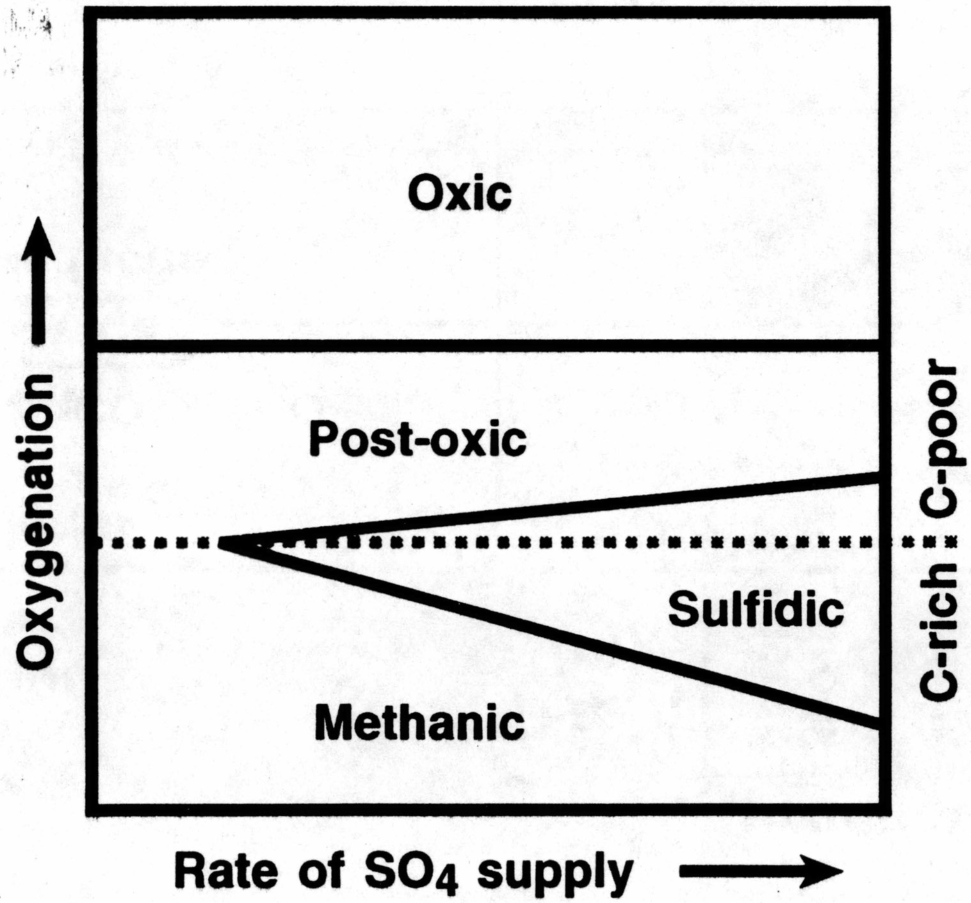
CONDITIONS FOR SIDERITE PRECIPITATION

- Low Eh
- High P_{CO_2}
- Low $[S^{-2}]$
- High $[Fe^{+2}]/[Ca^{+2}]$

GRI/BEG

QAa2311c

GEOCHEMICAL ENVIRONMENTS



From Maynard (1982)

GRI/BEG

QAa2485c

ORGANIC MATTER — DIAGENETIC ZONES

Zone	Depth (m)	CO_2 / HCO_3^- production: Microb. proc.	CO_2 / HCO_3^- production: Reduct. of Fe^{3+}	Carbonate $\delta^{13}C$ (‰ PDB)
Oxidation $CH_2O + O_2 \rightarrow CO_2 + H_2O$	0 to 0.01	-25 ‰		No ppt.
Post - oxic				0 to -25
Sulfate reduction $2CH_2O + SO_4^{-2} \rightarrow S^{-2} + 2CO_2 + 2H_2O$	0.01 to 10	-25 ‰	-25 ‰ ?	0 to -25
Methanogenesis $2CH_2O \rightarrow CH_4 + CO_2$	10 to 1000	+15 ‰		-10 to +15

GRI/BEG

After Curtis (1978)

QAa5293c

CANYON SIDERITE CEMENT

$\delta^{13}C$ (‰ PDB)

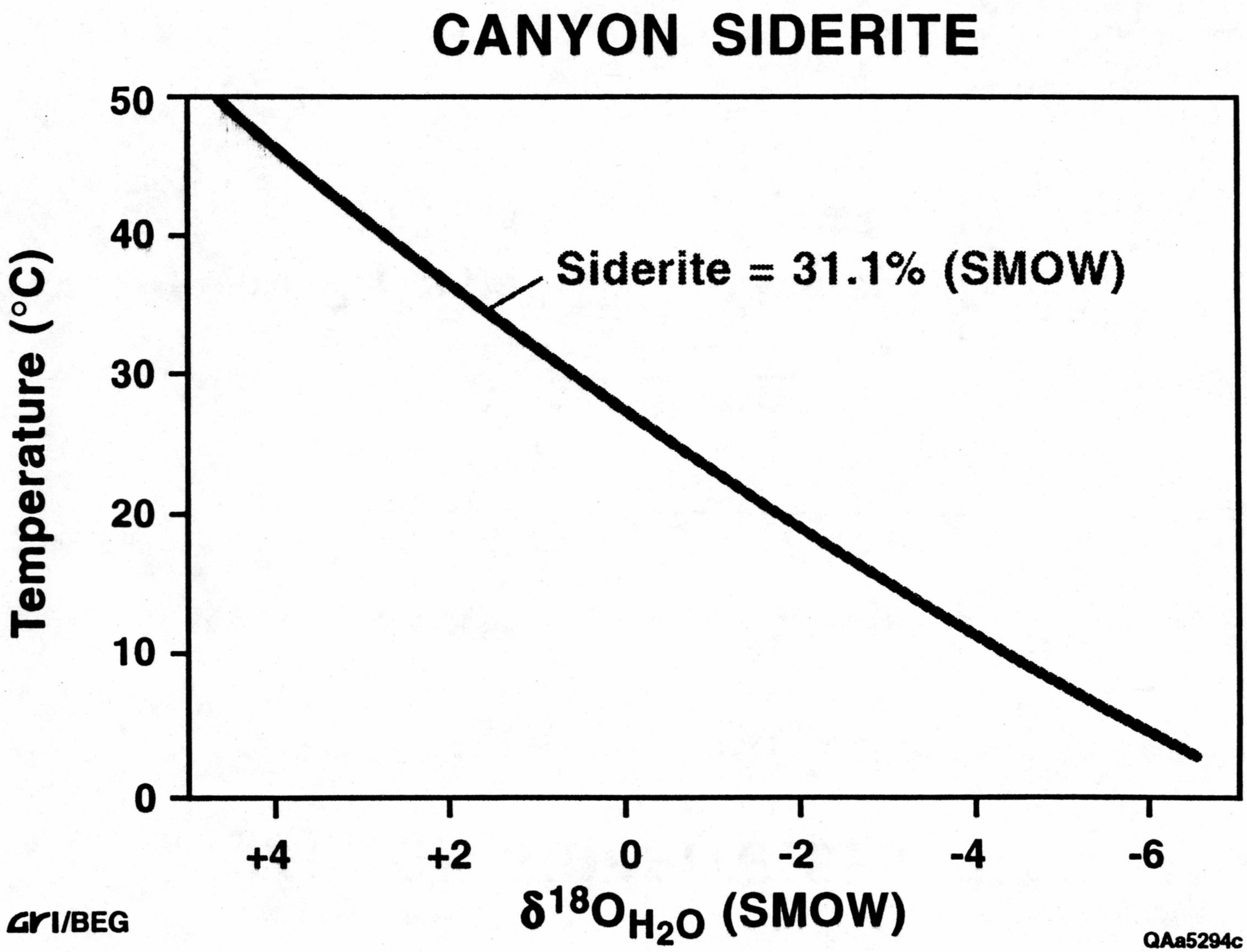
Range	Average
+0.6 to +4.0	+2.4

$\delta^{18}O$ (‰ PDB)

Range	Average
-0.7 to +1.2	+0.3

GRI/BEG

QAa5292c


CANYON SIDERITE
Siderite = 31.1% (SMOW)
Temperature (°C)
50
40
30
20
10
0
+4
+2
0
-2
-4
-6
$\delta^{18}O_{H_2O}$ (SMOW)
GRI/BEG
QAa5294c

COMPARISON OF RESERVOIR QUALITY IN CANYON SANDSTONES

	Siderite-rich (>10%)	Siderite-poor (<10%)
Porosity (%)	7.9	6.4
Permeability (md)		
Unstressed	0.069	0.014
Stressed	0.042	0.009
Quartz cement (%)	6	11
Minus-cement porosity (%)	33	16
No. samples	14	27

GRI/BEG

QAa2314c

CONCLUSIONS

- **Siderite rims formed during early burial (300 m) of Canyon deep-water marine sediments.**
- **Siderite precipitated in a methanic geochemical environment from sea-water-derived pore fluids.**
- **Siderite cement inhibited compaction and quartz cementation.**
- **Canyon sandstones with abundant siderite retain higher porosity and permeability.**

GRI/BEG

QAa2315c

NATURAL FRACTURES, SONORA CANYON

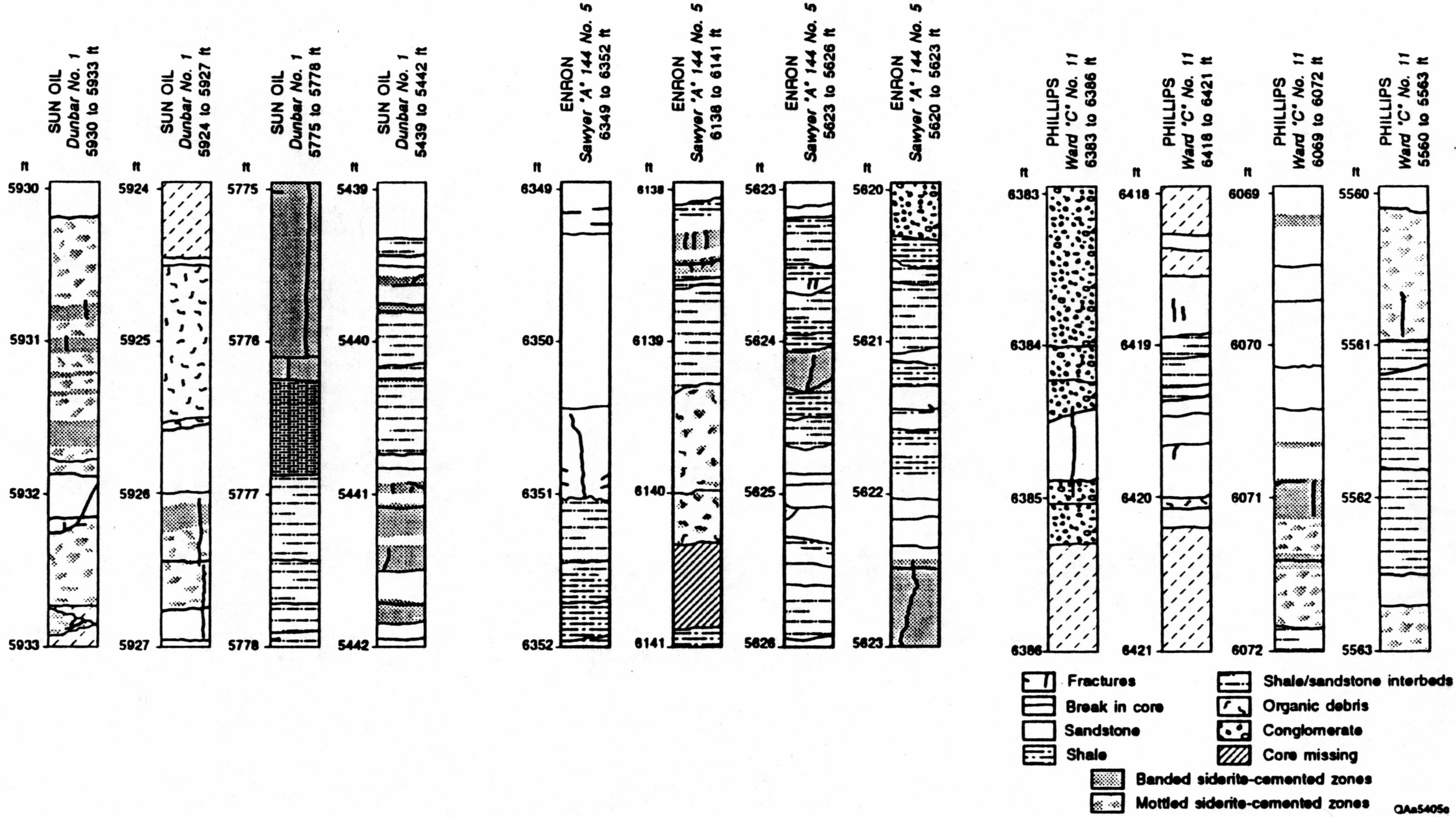
Presented by:

Stephen E. Laubach

Bureau of Economic Geology
The University of Texas at Austin
Austin, Texas

NATURAL FRACTURES
SUMMARY

- Documented in Three Wells
- 191 Natural Fractures in 435 ft of Sandstone
- 61% are in Siderite-Cemented Layers
- More Than 200 Drilling-Induced Fractures
- Some Natural Fractures are Permeable (RFT)
- Range of Strikes

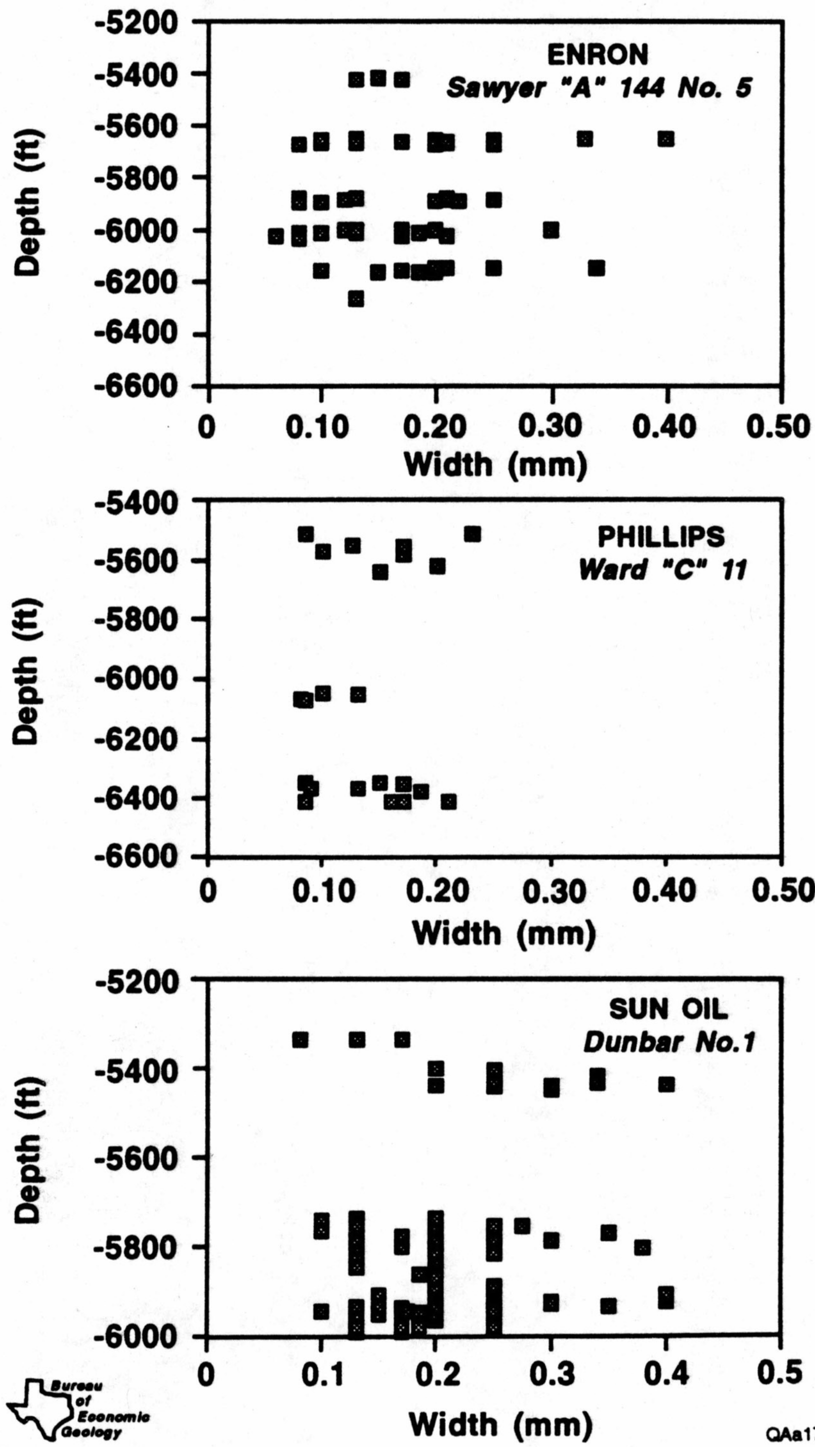


Examples of Natural Fractures in Sonora Canyon Core

FRACTURE ATTRIBUTES II

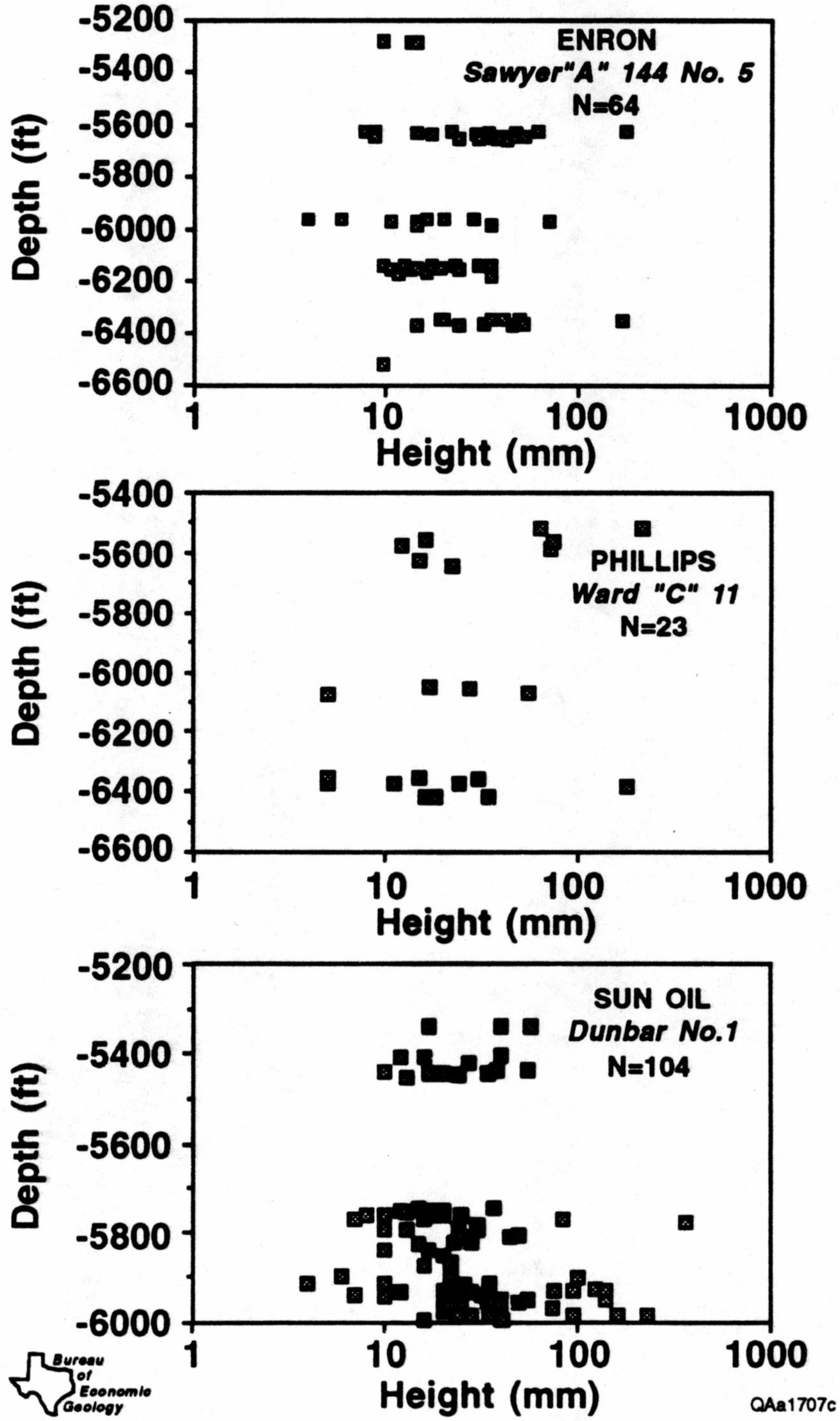
- Fractures are Short:
  - Many Less Than 3 Inches Tall
  - Few More Than 1 ft
- End at Shale Interbeds or Cement Boundaries
- Little Vertical Interconnection
- Spacing: Several Inches to Tens of Feet

FRACTURE WIDTH vs DEPTH
CANYON SANDSTONE



QAa1708c

FRACTURE HEIGHT vs DEPTH
CANYON SANDSTONE



FRACTURE CLASSES

Fractures Only in Siderite-Cemented Zones

Fractures Primarily Outside Siderite Zones

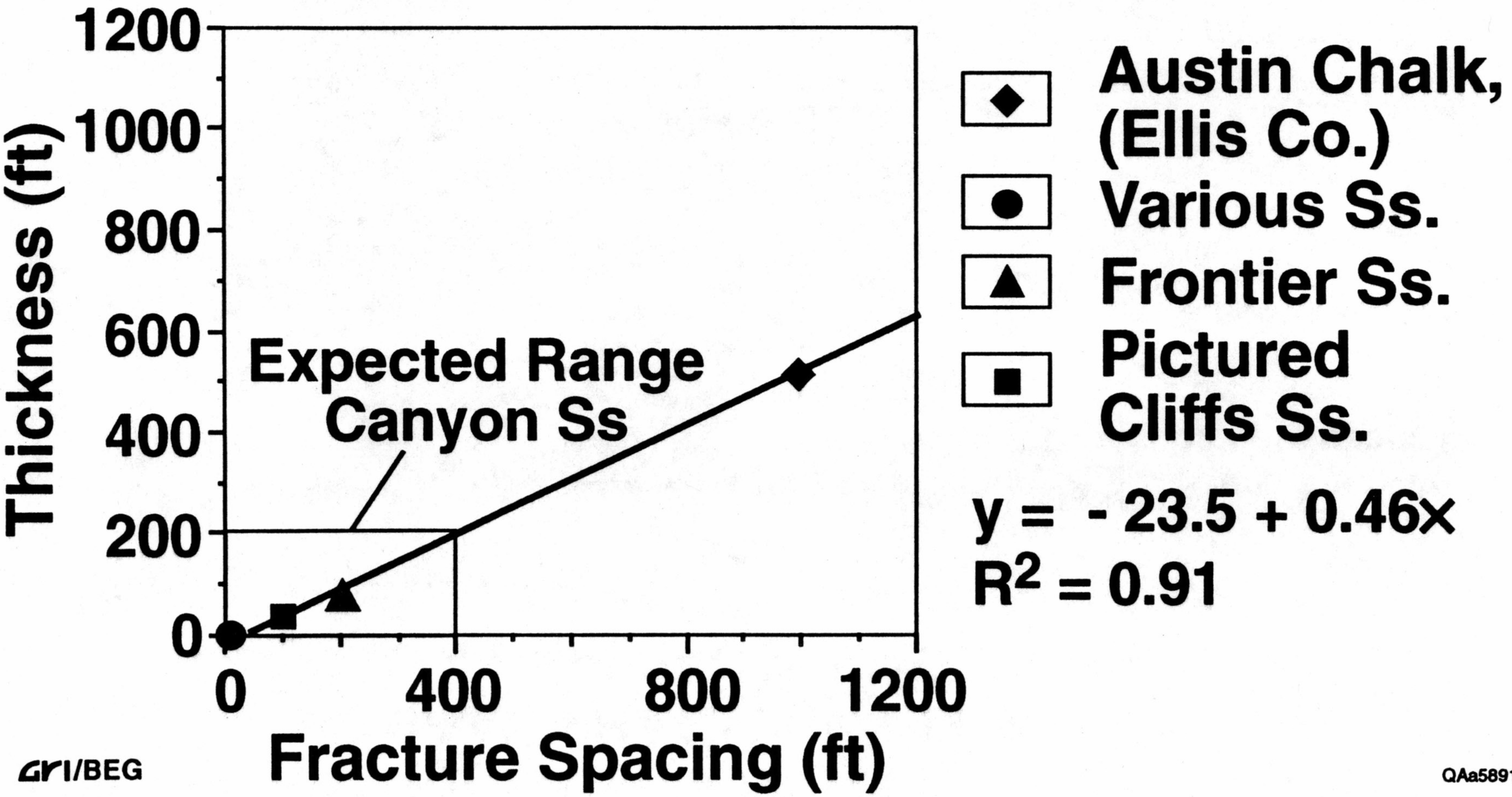
Quartz Filled

Quartz and Calcite Filled

GRI/BEG

QAa5933c(b)

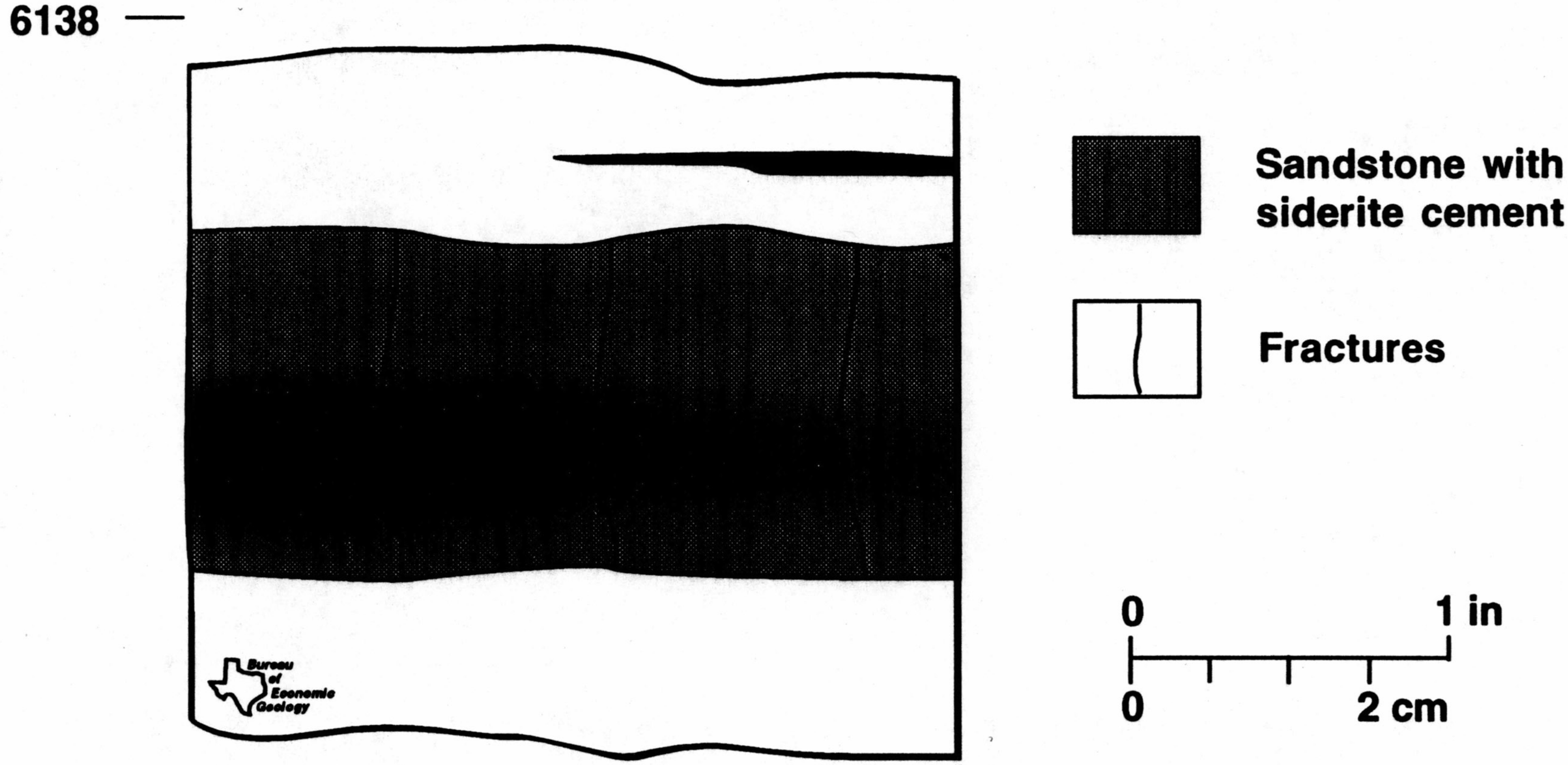
FRACTURE SWARM SPACING VS. UNIT THICKNESS



GRI/BEG

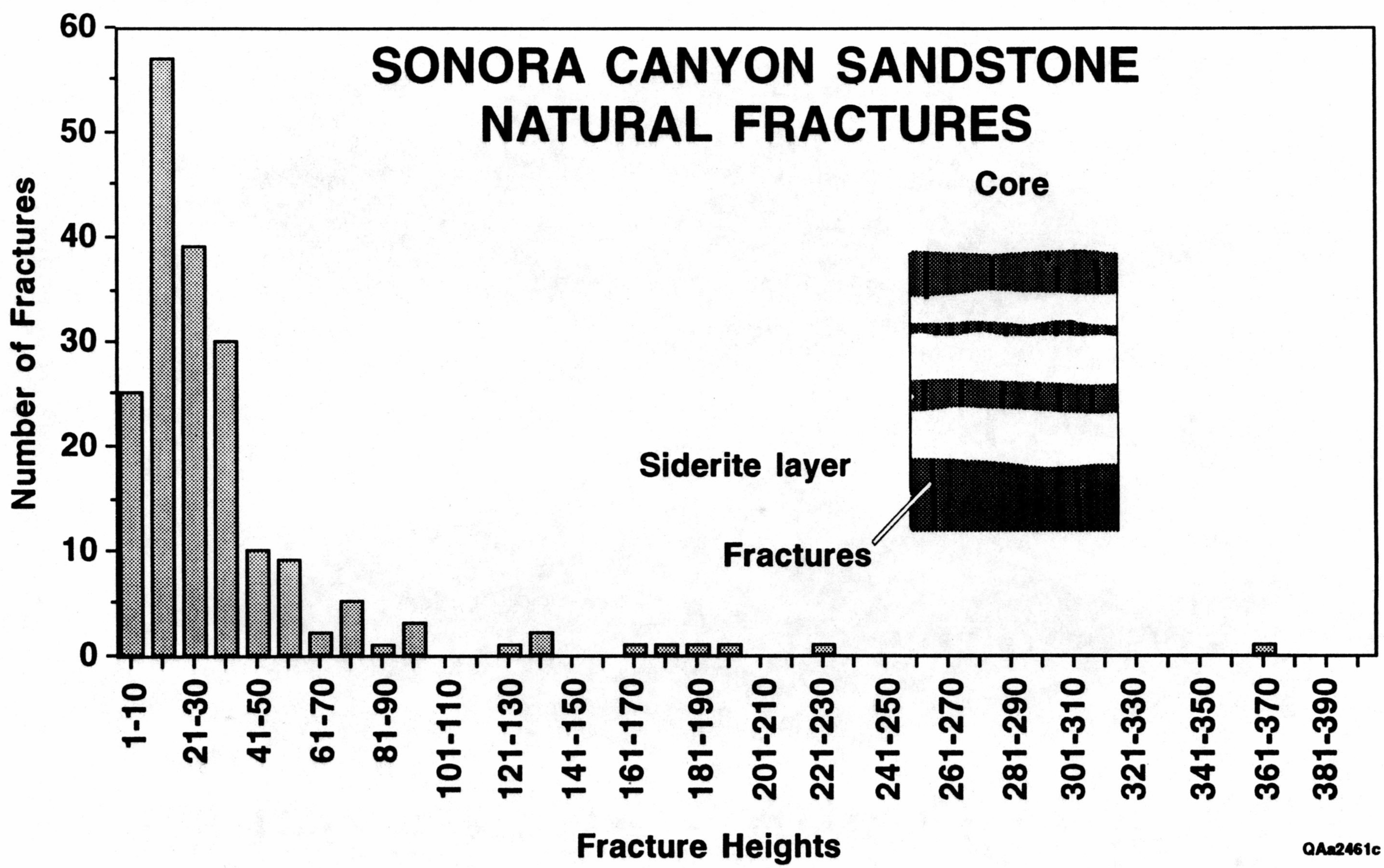
QAa5891c

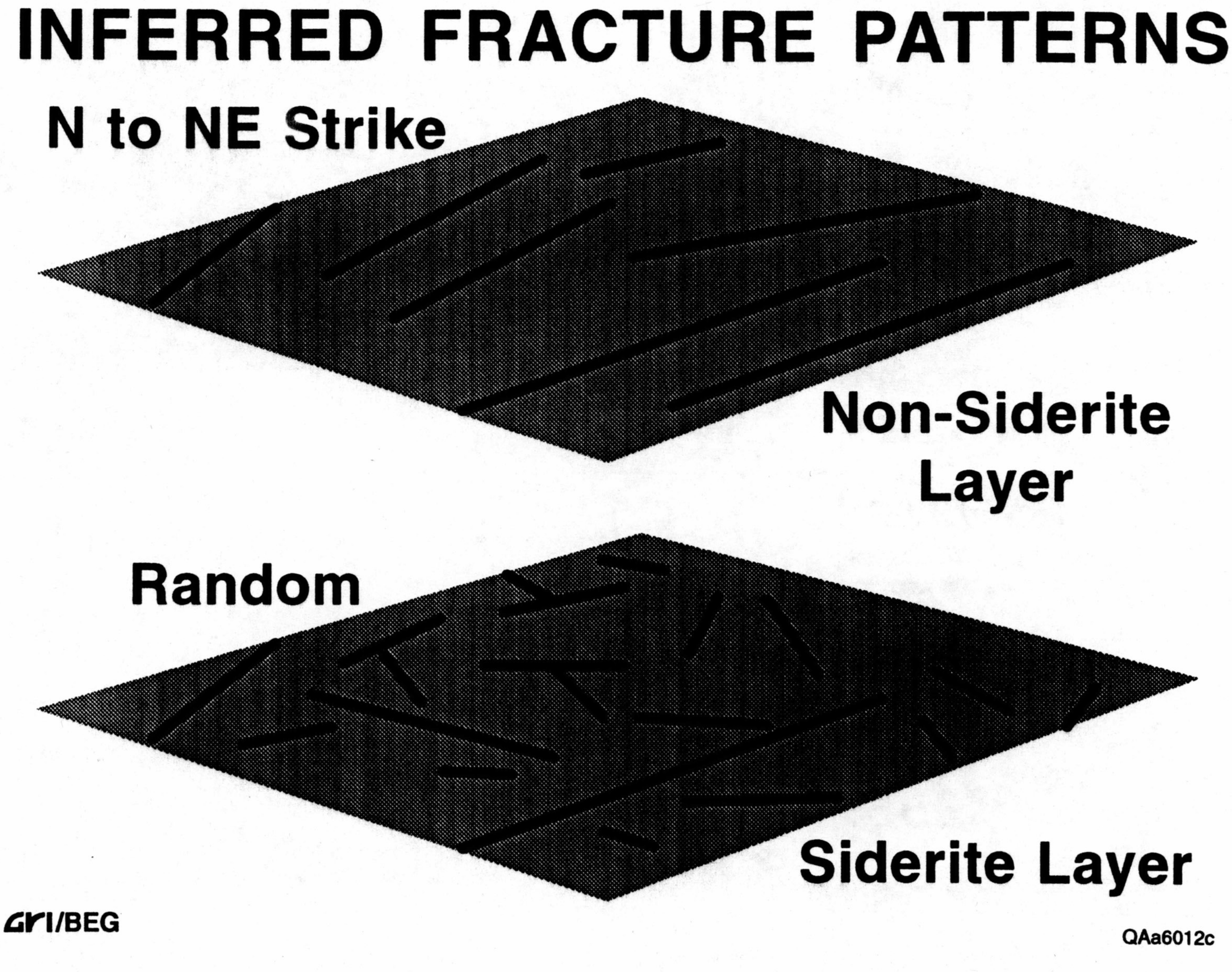
NATURAL FRACTURES LOCALIZED IN SIDERITE-CEMENT ZONES



CORE SKETCH
Enron
Sawyer "A" 144 No. 5

QAa1712c


SONORA CANYON SANDSTONE
NATURAL FRACTURES
Core
Siderite layer
Fractures
Number of Fractures
0
10
20
30
40
50
60
1-10
21-30
41-50
61-70
81-90
101-110
121-130
141-150
161-170
181-190
201-210
221-230
241-250
261-270
281-290
301-310
321-330
341-350
361-370
381-390
Fracture Heights
QAa2461c

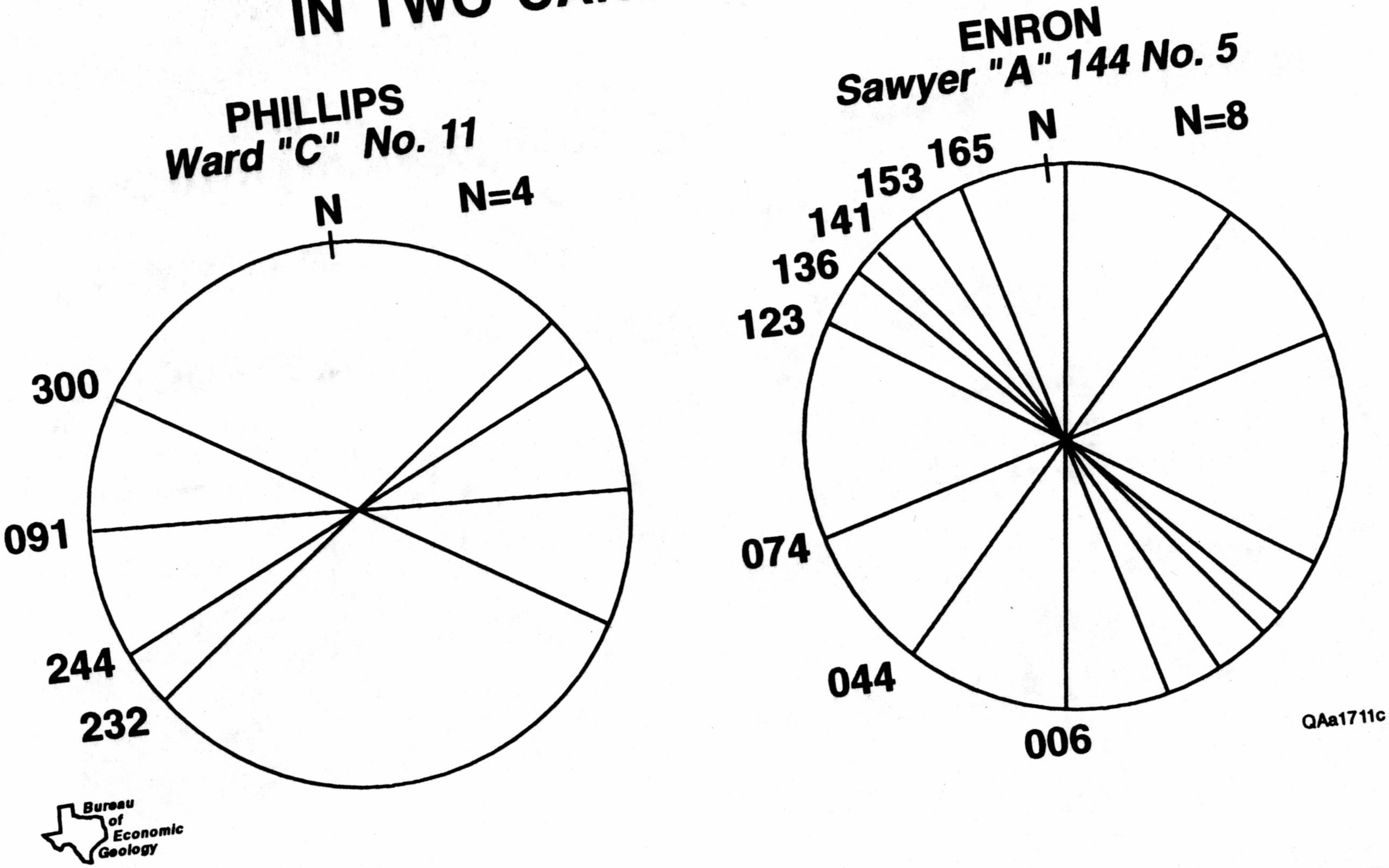

INFERRED FRACTURE PATTERNS
N to NE Strike
Non-Siderite
Layer
Random
Siderite Layer
GRI/BEG
QAa6012c

FRACTURE STRIKE

- Northeast and Northwest Strikes
- Northeast Grain Dominant
- Some Layers May Have Random Strikes

GRI/BEG QAa6016c (d)

NATURAL FRACTURE STRIKES IN TWO CANYON WELLS



FRACTURE ORIENTATIONS FROM CORE DATA

PHILLIPS
Ward "C" No. 11

Fracture #	Depth (ft)	Azimuth	Comments
N-16	5646.75	300	1
N-20	5560.80	091	1
N-22	5516.65	244	1, 3
N-23	5515.68	232	1, 3

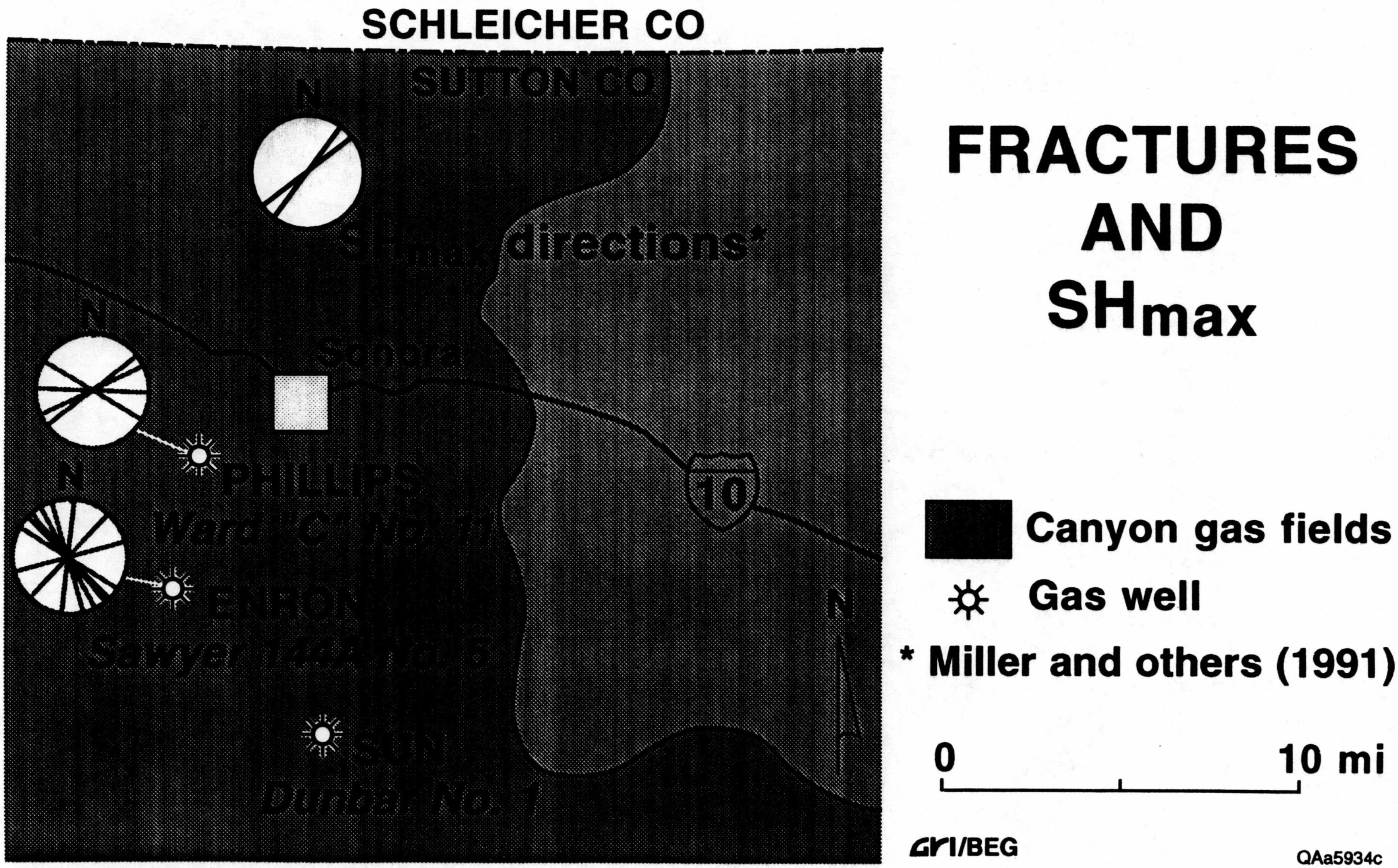
ENRON
Sawyer "A" No. 144-5

Fracture #	Depth (ft)	Azimuth	Comments
N-33	5969.93	006	1
N-34	5968.78	165	1
N-35	5968.72	074	1
N-36	5960.30	141	1, 4
N-38	5958.08	123	2
N-39	5958.08	153	2
N-40	5957.35	044	1
NI-1	5957.35	044	5

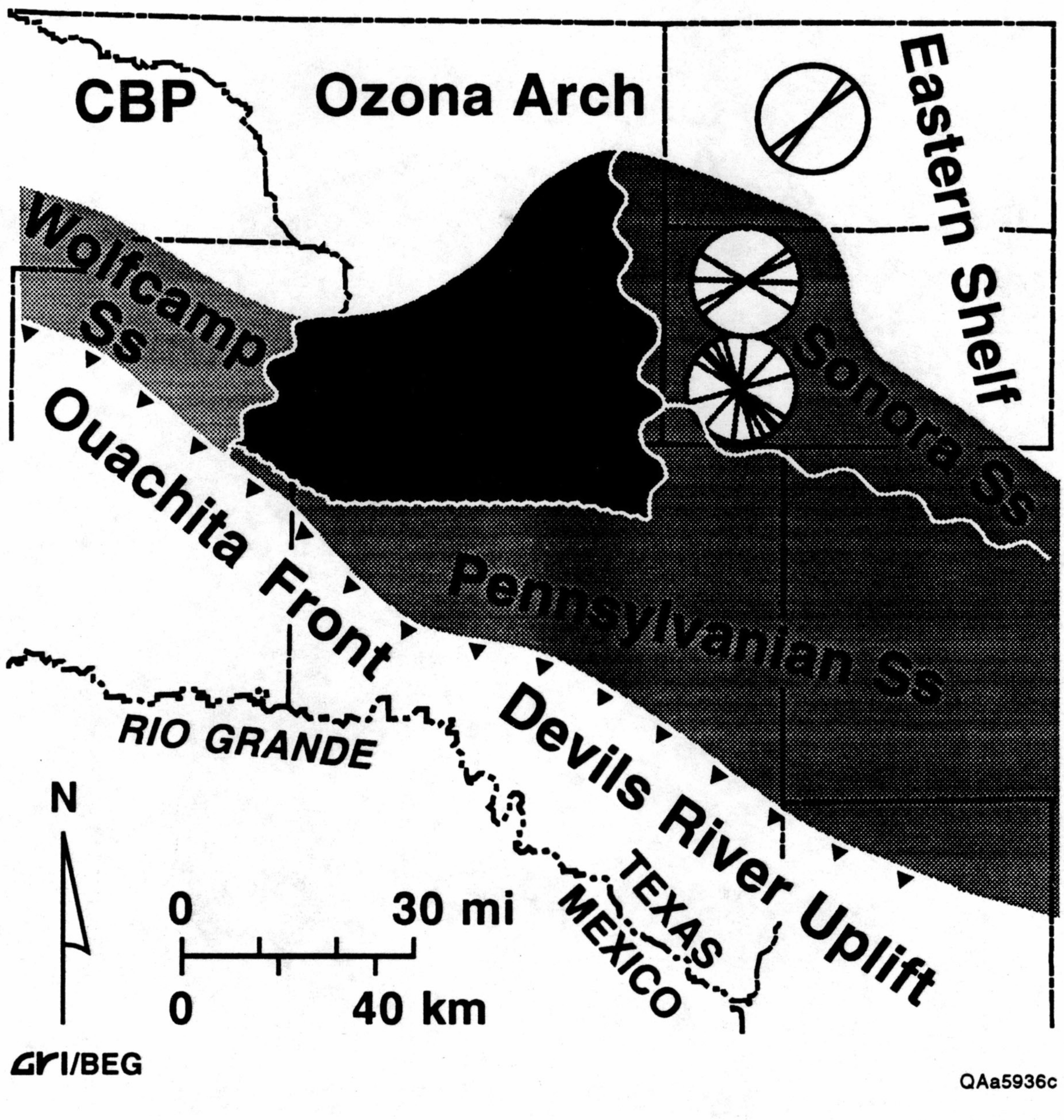
Comments
1. Fracture in siderite-cemented layer
2. Fracture in shale
3. Fracture in same cored interval
4. Orientation uncertain
5. Possibly a drilling-induced fracture

Bureau of Economic Geology

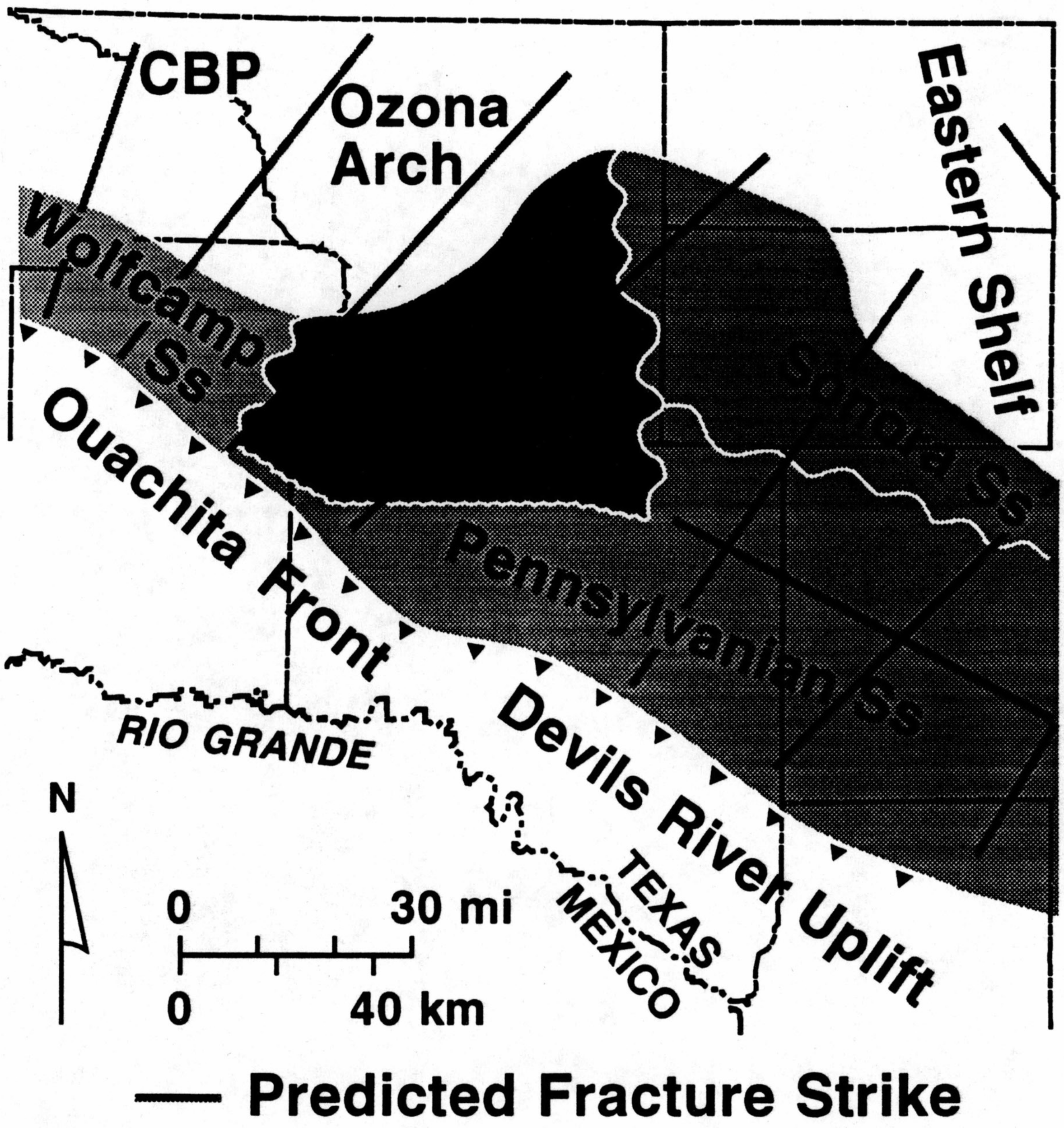
QAa1709c


SCHLEICHER CO
SUTTON CO
N
N
N
Sonora
PHILLIPS
Ward "C" No. 1
ENRON
Sawyer 144A No. 5
SUN
Dunbar No. 1
10
N
FRACTURES AND SHmax
Canyon gas fields
Gas well
* Miller and others (1991)
0
10 mi
GRI/BEG
QAa5934c

OBSERVED FRACTURE STRIKES



PREDICTED FRACTURE STRIKES — LATE

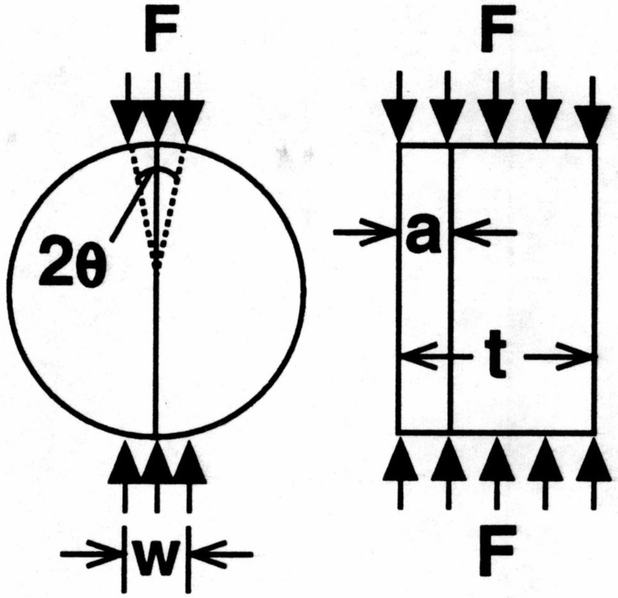


GRI/BEG

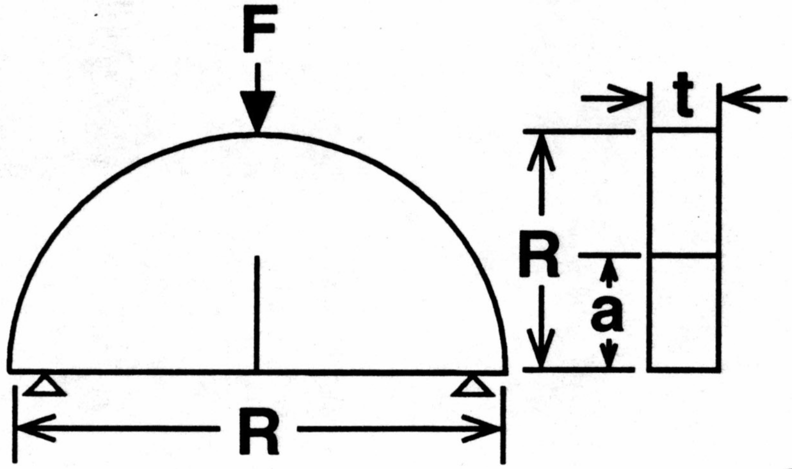
QAa5935c

SPECIMEN GEOMETRIES USED FOR DETERMINING FRACTURE TOUGHNESS

NOTCHED BRAZILIAN DISC SPECIMEN



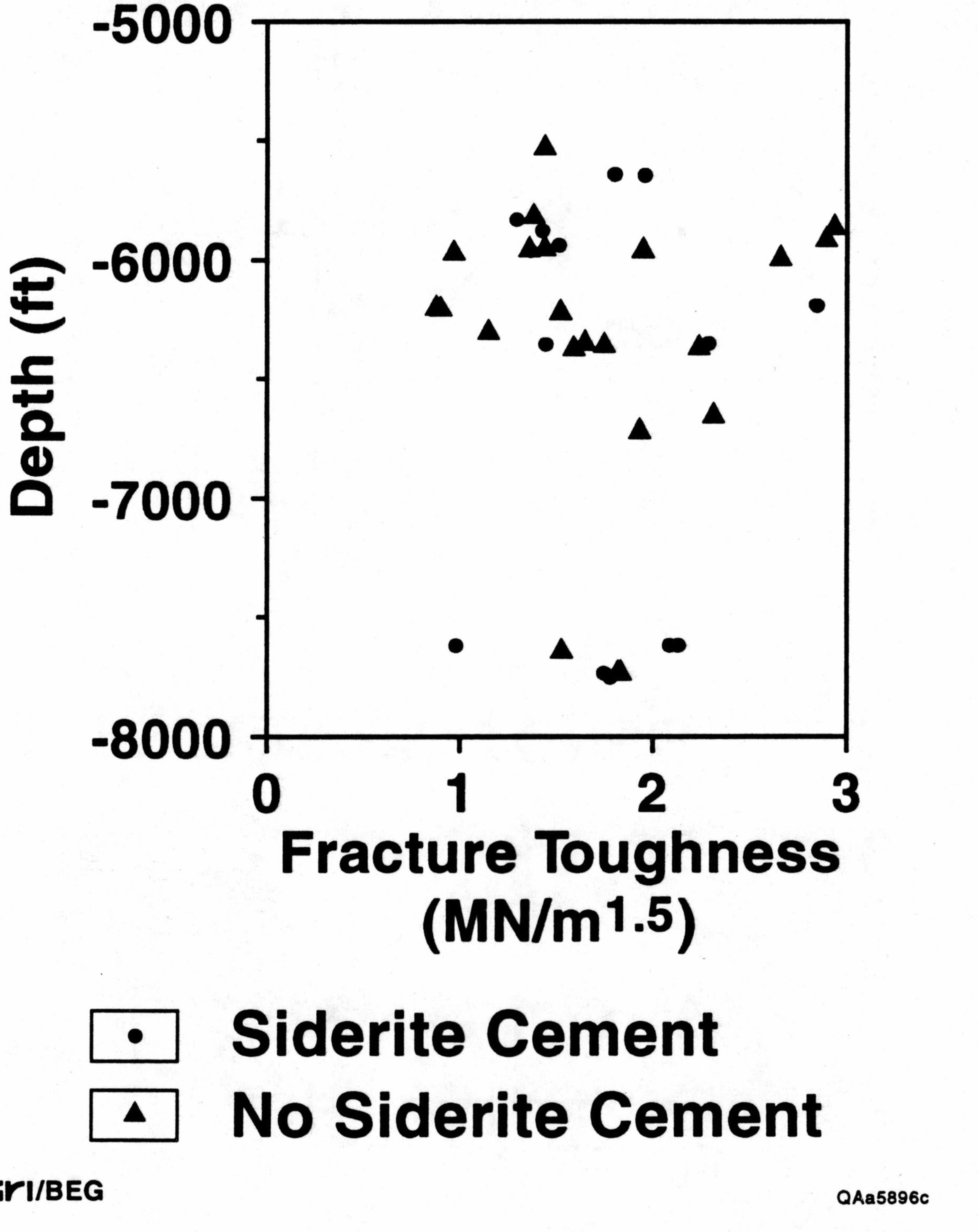
SEMI-CIRCULAR BEND SPECIMEN



GRI/BEG

QAa5898c

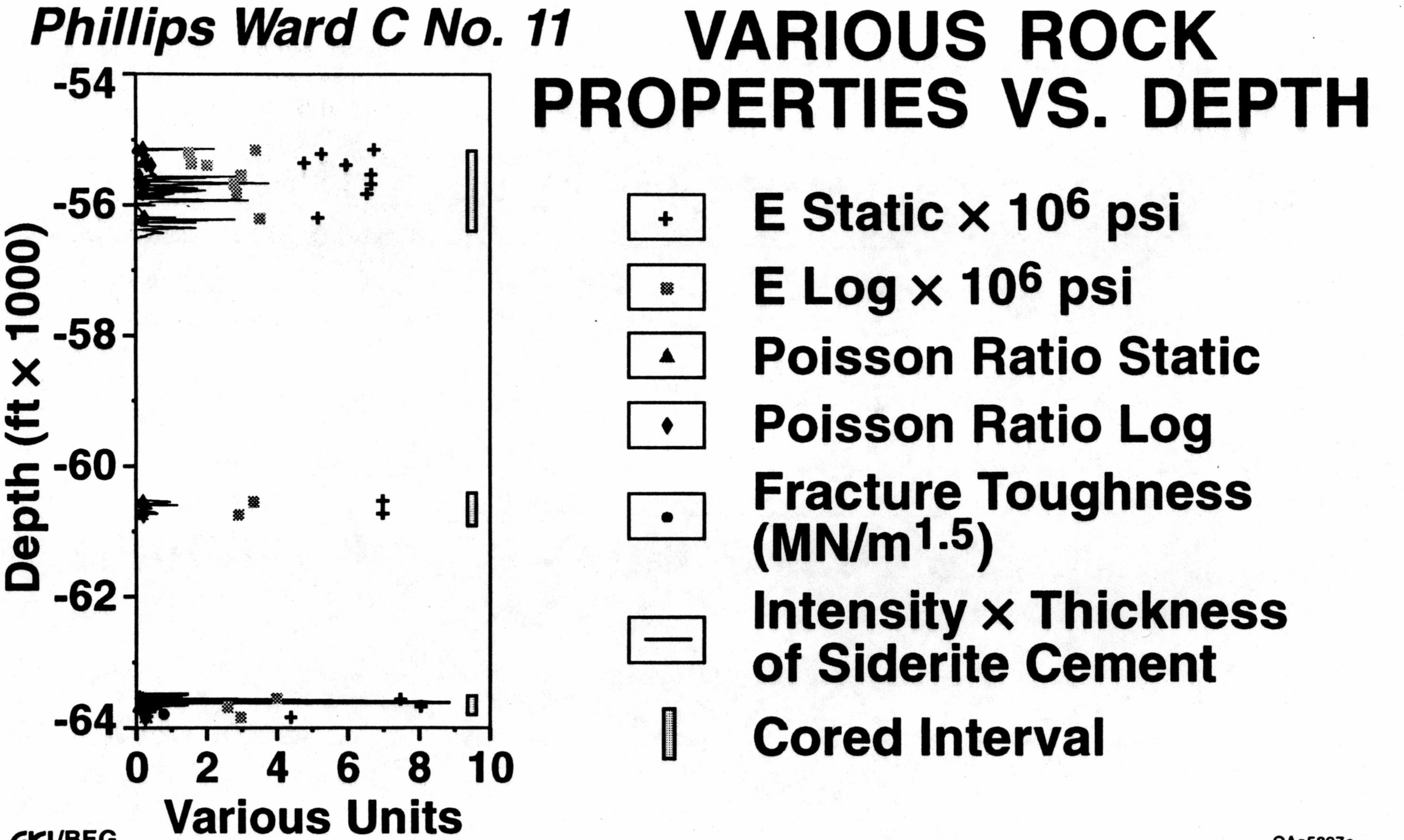
FRACTURE TOUGHNESS VS. DEPTH



GRI/BEG

QAa5896c

VARIOUS ROCK PROPERTIES VS. DEPTH



GRI/BEG

QAa5897c

SONORA CANYON FRACTURES

Targets for Horizontal Drilling?

Limited Vertical Connectivity (Narrow Targets)

Effect on Hydraulic Fracture

Fracture Branching/Near-Wellbore Tortuosity

STRESS MEASUREMENTS AND SUMMARY OF GRI COOPERATIVE WELL DATABASE

Presented by:

Robin Hill

CER Corporation

Las Vegas, Nevada

Database Development
Lower, Middle and Upper Canyon Sands

Oriented core

Wireline logs

Routine and special core analyses

In-situ stress measurements

Pre- and post-frac well tests

Minifrac and propped frac treatment monitoring

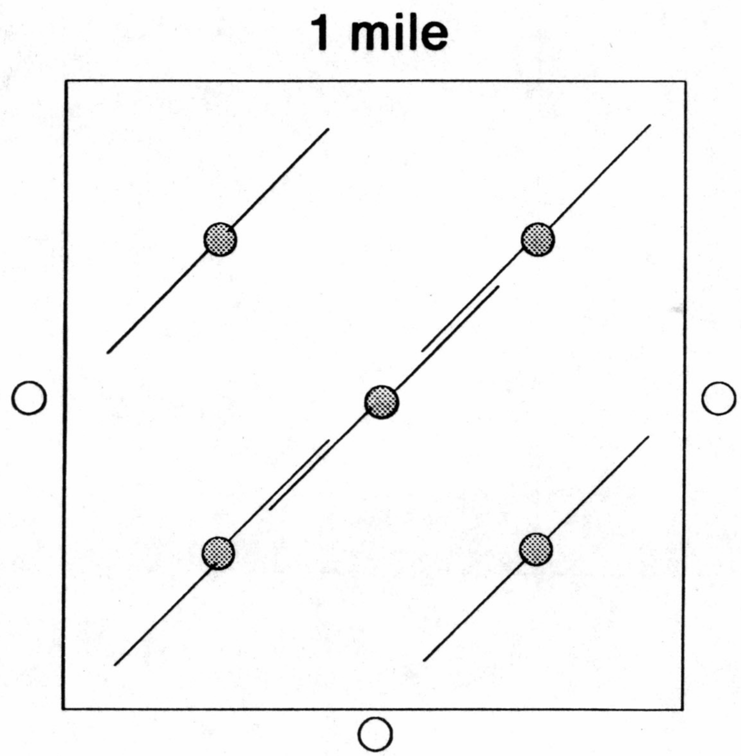
Fracture diagnostics

Research Focus

Acquisition and analysis of data to assist producers in resolving technical challenges in the Canyon Sands:

- **Improved geological characterization**
- **Improved payzone identification**
- **Determination of hydraulic fracture azimuth**
- **Quantification of stresses in sands and shales**
- **Development of a more effective stimulation treatment**

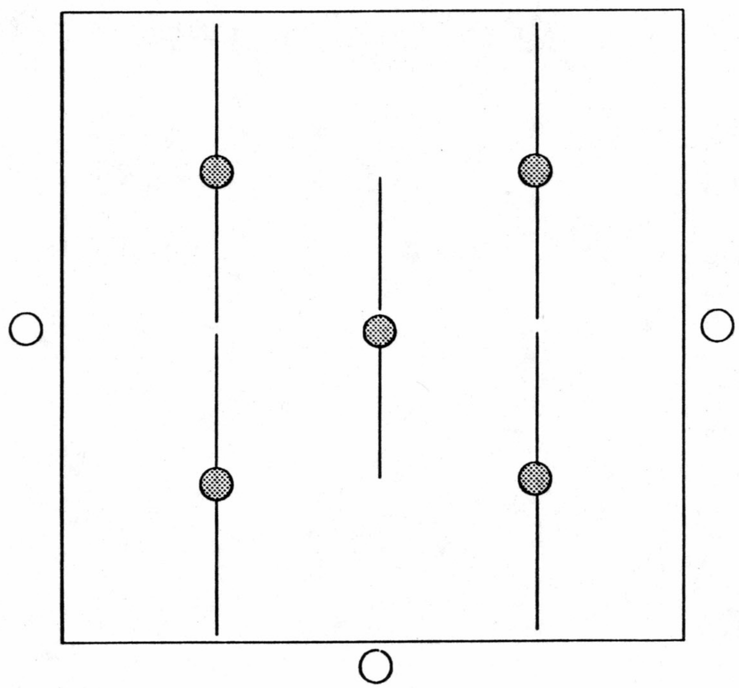
Importance of Fracture Azimuth (poor drainage scenario)



assumes northeast-southwest fracture azimuth

Importance of Fracture Azimuth
(optimum drainage scenario)

1 mile

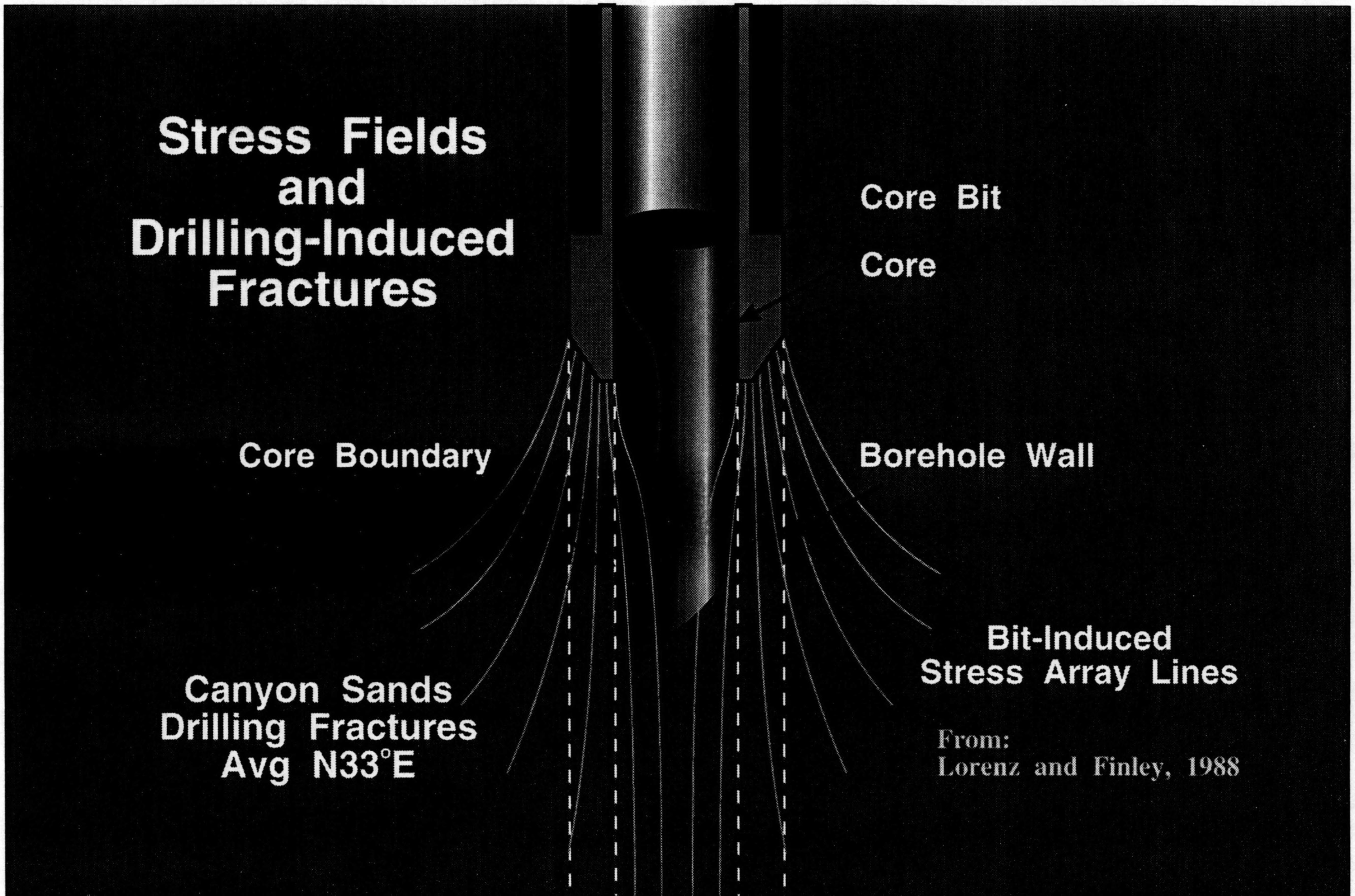


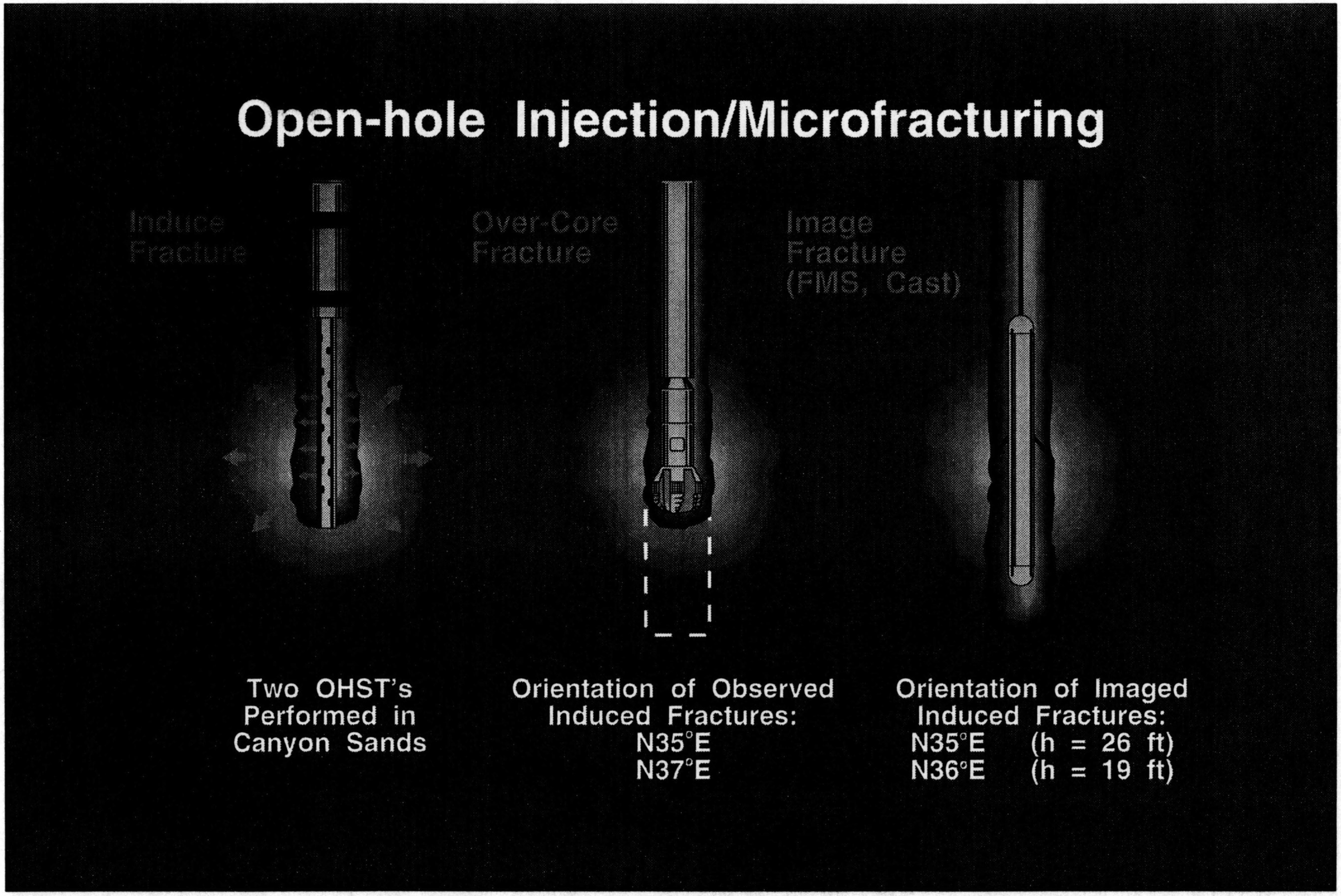
assumes north-south fracture azimuth

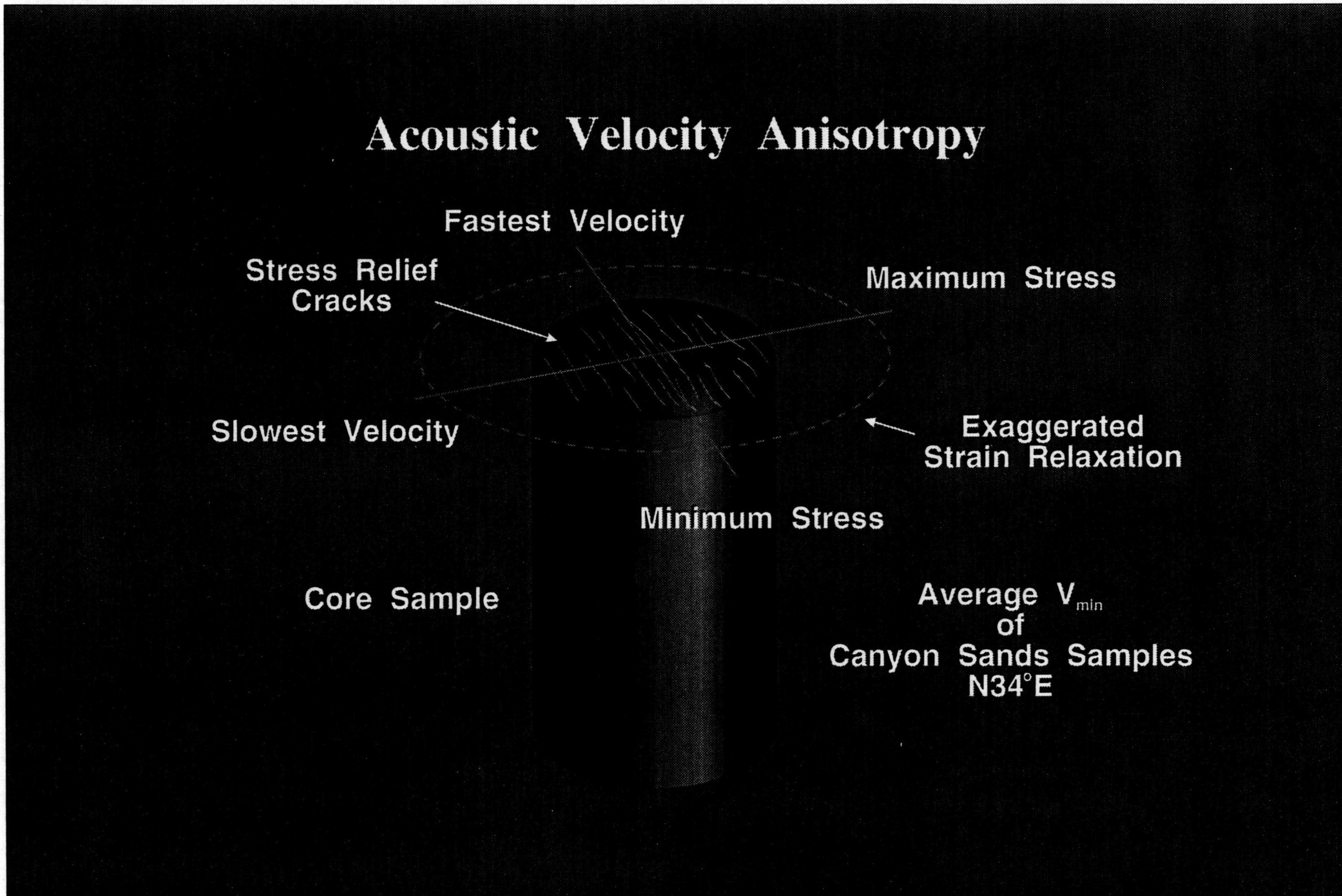
Prediction and Measurement of Hydraulic Fracture Azimuth

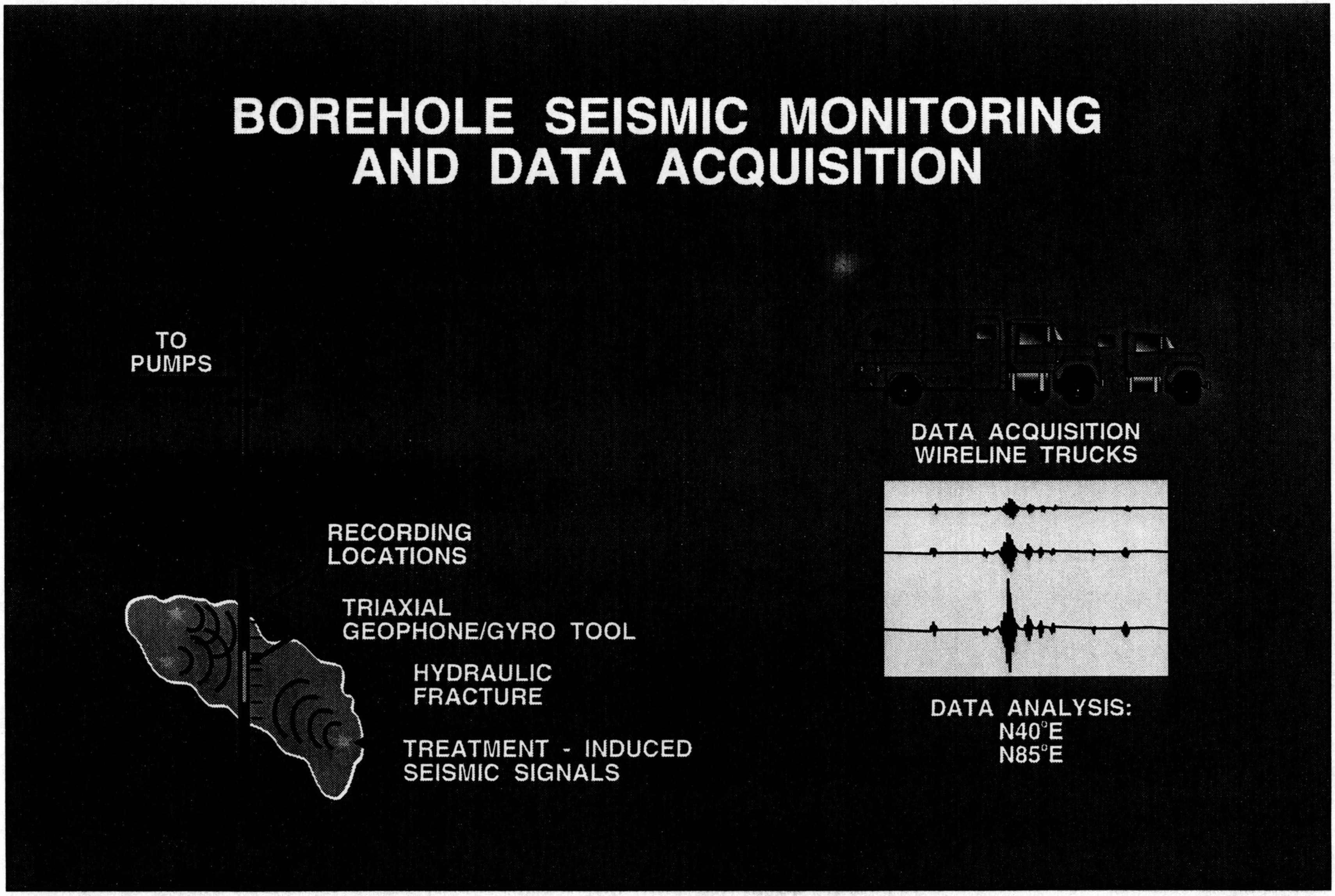
Techniques Applied

1. Direct observation and orientation of an induced fracture
2. Borehole imaging of an induced fracture
3. Measurement and correlation of drilling-induced fractures
4. Borehole breakouts/elongation
5. Acoustic velocity anisotropy
6. Anelastic strain recovery
7. Borehole microseismic survey
8. Oriented gamma ray survey of tagged frac


Stress Fields
and
Drilling-Induced
Fractures
Core Bit
Core
Core Boundary
Borehole Wall
Bit-Induced
Stress Array Lines
Canyon Sands
Drilling Fractures
Avg N33°E
From:
Lorenz and Finley, 1988


Open-hole Injection/Microfracturing
Induce Fracture
Over-Core Fracture
Image Fracture (FMS, Cast)
Two OHST's Performed in Canyon Sands
Orientation of Observed Induced Fractures: N35°E N37°E
Orientation of Imaged Induced Fractures: N35°E (h = 26 ft) N36°E (h = 19 ft)


Acoustic Velocity Anisotropy
Fastest Velocity
Stress Relief Cracks
Maximum Stress
Slowest Velocity
Exaggerated Strain Relaxation
Minimum Stress
Core Sample
Average V_{min} of Canyon Sands Samples N34°E


BOREHOLE SEISMIC MONITORING
AND DATA ACQUISITION
TO
PUMPS
DATA ACQUISITION
WIRELINE TRUCKS
RECORDING
LOCATIONS
TRIAXIAL
GEOPHONE/GYRO TOOL
HYDRAULIC
FRACTURE
TREATMENT - INDUCED
SEISMIC SIGNALS
DATA ANALYSIS:
N40°E
N85°E

FRACTURE AZIMUTH RESULTS
PHILLIPS AND ENRON CO-OP WELLS

TECHNIQUE	AVG. AZIMUTH PPCo	AVG. AZIMUTH EOG
OVER-CORED OHST	035°	037°
IMAGED OHST FRACTURE	035°	036°
DRILLING-INDUCED FRACTURES	035°	033°
BOREHOLE BREAKOUTS	---	046°
ACOUSTIC ANISOTROPY	034°	---
ANELASTIC STRAIN RECOVERY	095°	---
CMR SURVEY	040°; 085°	---
ORIENTED POST-FRAC GR	?	---

Fracture Azimuth in the Canyon Sands
Conclusions

- ✓ Knowledge of hydraulic fracture azimuth becomes increasingly important as well spacing decreases and this information can be used to design well placement

- ✓ Multiple techniques indicate that hydraulic fracture azimuth in the Canyon Sands is within the N30E to N40E range

- ✓ The techniques applied are all commercially available and the methodology can be applied to any project where knowledge in in situ stress directions is important

Techniques for Determining Subsurface Stress Direction

- Core Based
- Borehole Based
- Hydraulic Fracture Monitoring
- Regional Geologic Indicators

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This report is available at the University of Houston's Natural Gas Supply Information Center at the following address:

University of Houston
Dobrin Memorial Library
Houston, Texas 77204-4231
713/ 743-9158
Fax 713/ 743-9164

In Situ Stress Testing

Purposes

- To Characterize Vertical In Situ Stress Variations to Evaluate Fracture Height Growth

- To Evaluate Which Zones to Perforate to Maximize Hydraulic Fracture Coverage

- Use this Information to Improve Fracture Treatment Designs

Canyon Sanstone Stress Measurements

- 12 Intervals Tested — 3 OHST's and 9 CHST's

- Equally Distributed Between Sandstones and Shales

- OHST's — Overcore Created Fracture (Azimuth)
  See Today's Core Display

- CHST's — Mechanically Easier and Less Expensive

Stress Test Results are summarized in GRI Topical Reports

Conclusions From Stress-Magnitude Studies

- OHST's and CHST's provide a means of determining in situ stress

- BHP measurements with DHSI are required to insure accurate data

- Stress measurements are required to calibrate log predictions

- Detailed, representative stress profiles can be generated

- Stress contrasts of 800 to 1,100 psi exist between sandstone and shale

- Despite stress contrast fracture containment is not sure because shale layers are thin

- Used with 3-D fracture models, stress profiles are helpful for fracture treatment design

SUMMARY OF DATA ACQUISTION
PHILLIPS PETROLEUM WARD C-11
Block B; H.E.&W.T. RR Co. Survey
Sutton Co., TX

Conventional Core
- 5,515 to 6,422ft (201 ft; 128 ft oriented)
- Core Photographs

Core Analyses
- Routine petrophysical analyses (stressed porosity and permeability, fluid saturations, grain density on 199 samples)
- Special analyses (electrical properties, mechanical properties, relative permeability)
- Anelastic strain recovery (8 samples)
- Acoustic anisotropy data (5 samples)
- Detailed core descriptions (lithology and fractures)
- Thin section petrography (26 samples)

Openhole Stress Tests (5,429 ft; 6,050 ft)
- Fracture closure pressure data

Wireline Logs (Openhole)
- Spectral Density/Dual Spaced Neutron/Compensated Spectral Gamma Ray; Circumferential Acoustic Scanning Tool/Oriented Caliper/Sequential Formation Tester (HLS)
- Electromagnetic Propagation Tool/Microlog/Dual Laterolog/MicroSFL/Digital Sonic (SWS)

Casedhole Stress Tests
- Bottomhole pressure data; 6,519 ft; 6,569 ft; 6,619 ft; 6,709 ft (lower Canyon Sands interval)
- Bottomhole pressure data; 6,367 ft; 6,410 ft (middle Canyon Sands interval)

Fracture Fluids Laboratory Tests
- Conductivity, regained permeability, static fluid loss data of Canyon Sands core using 4 frac fluid types

Well Tests
- Pre-frac flow and pressure buildup test data in the lower Canyon Sands interval (6,338 - 6,651 ft)
- Pre-frac/post-frac flow and pressure buildup test in the middle Canyon Sands interval (6,260 - 6,651 ft)

Minifrac and Fracture Treatment Monitoring
- Main frac treatment data (time, injection rate, bottomhole pressure, proppant concentration) from the lower Canyon Sands completion interval (6,338 - 6,651 ft)
- Minifrac/main frac treatment data from the middle Canyon Sands completion interval (6,260 - 6,651 ft)

Fracture Diagnostics
- Continuous Microseismic Radiation survey (Teledyne Geotech) for fracture height and azimuth in the middle Canyon Sands completion interval
- R/A logging, temperature logging data for correlative fracture height data in the middle Canyon Sands completion interval
- RotaScan (oriented gamma ray data) in middle Canyon Sands interval - HLS
- Overcored and imaged open-hole stress test induced fracture (see core and log data)

SUMMARY OF DATA ACQUISTION
ENRON OIL & GAS SAWYER A-144 NO. 5
Sec. 144, Block C; H.T.&E RR Co. Survey
Sutton Co., TX

Conventional Core
- 5,275 to 6,580 ft (305 ft, 27.5 ft oriented)
- Core photographs

Core Analyses
- Routine (stressed porosity and permeability, fluid saturations, grain density)
- Detailed fracture descriptions (lithology and fractures)

Openhole Stress Test (5,957 ft)
- Bottomhole pressure data
- Induced fracture overcored

Wireline Logs (Openhole - air filled)
- High Resolution Temp/Spectral Density/Dual Spaced Epithermal Neutron/Compensated Spectral Gamma Ray/Dual Induction/Sidewall Neutron (HLS)

Wireline Logs (Openhole - fluid filled)
- Spectral Density/Dual Spaced Neutron/Compensated Spectral GR (HLS)
- Dual Laterolog/MicroSFL/Electromagnetic Propagation/Microlog Formation Microscanner/Digital Array Sonic/Repeat Formation Tester (SWS)

Casedhole Stress Tests
- Bottomhole pressure data; 6,384 - 86ft; 6,492 - 94ft; 6,594 - 96ft (lower Canyon Sands interval)

Well Tests
- Pre-frac/post-frac flow and pressure buildup test data; 6,375 - 6,518 ft (lower Canyon Sands)
- Pre-frac/post-frac flow and pressure buildup test data; 5,921 - 6,212 ft (middle Canyon Sands)
- Pre-frac/post-frac flow and pressure buildup test data; 5,281 - 5,439 ft (upper Canyon Sands)

Minifrac and Fracture Treatment Monitoring
- Minifrac/main frac treatment data (injection rates, pressures, time proppant concentration); lower Canyon Sands completion interval
- Minifrac/main frac treatment data (injection rates, pressures, time proppant concentration); middle Canyon Sands completion interval
- Minifrac/main frac treatment data (injection rates, pressures, time proppant concentration); upper Canyon Sands completion interval

Fracture Diagnostics
- R/A logging, temperature logging data for fracture height data in the lower Canyon Sands completion interval
- Overcored and logged open-hole stress test fracture (see core data, log data)

Injection Rate/Crossflow Experiment
- relative injection rate data in intervals having different stresses, measured by spinner/pressure tool; upper Canyon Sands completion interval
- crossflow data between perforated intervals using spinner/pressure tool; upper Canyon Sands completion interval

REVIEW OF OPERATOR RESULTS

and

IDENTIFICATION OF DEVELOPMENT CHALLENGES

SURVEY OF CANYON OPERATORS

- Active in Both Sonora and Ozona
- Classify Canyon as a Development Play
- 6 to 40 Years Canyon Experience
- 10 to 50 Canyon Wells per Year
- Optimistic About Future
  - Low Drilling Costs
  - Abundant Reserves
  - Drilling Opportunities

CANYON GEOLOGY
OPERATOR'S PERSPECTIVE

- **Submarine-Fan Depositional Environment**

- **Geologic Research Primary Component of Development Strategies**

- **Pay Zones Identified with Neutron/Density and Temperature Logs**

- **Sandstone Thickness Maps Are Basic Geological Data For Well Location**

- **Innovative Mapping Techniques also Used**

OPERATORS IDENTIFY GEOLOGIC CHALLENGE

- **Predicting Sandstone Distribution**
- **Predicting Permeability Distribution**
- **Documenting Reservoir Architecture**
- **Dealing with Sand/Shale Lamination**
- **Recognizing Contributing Pay**
- **Predicting Reservoir Fluids**

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