PEER REVIEW OF UNCONVENTIONAL GAS RECOVERY

MULTIWELL EXPERIMENTS

June 26-28, 1984
Key Bridge Marriott Hotel
Arlington, Virginia

********** AGENDA **********

ALL MEETINGS WILL BE HELD IN THE FRANCIS SCOTT KEY MEETING ROOM ON THE LOWER LOBBY LEVEL.

Tuesday June 26 1984

7:30 - 8:15 a.m.	Breakfast at the View Restaurant on the 14th floor.
8:30 - 8:40 a.m.	Welcome and Introduction Douglas B. Uthus. Director Office of Oil, Gas and Shale Technology U.S. Department of Energy
8:40 - 8:50 a.m.	Peer Review Procedures and Schedule Judith Kimel, Session Coordinator Applied Management Sciences, Inc.
8:50 - 9:40 a.m.	Overview of the Unconventional Gas Recovery Program Charles A. Komar Morgantown Energy Technology Center
9:40 - 10:30 a.m.	Overview. of the Western Gas Sands Subprogram Karl H. Frohne Morgantown Energy Technology Center
10:30 - 10:45 a.m.	Break
10:45 - 11:35 a.m.	Overview of Multiwell Experiments David A. Northrop Sandia National Laboratories
11:35 a.m. - 12:25 p.m.	Multiwell Experiments - An Operational Overview Robert L. Mann CER Corporation
12:25 - 2:00 p.m.	Lunch

Tuesday (Continued)

2:00 p.m.	Hospitality Suite is open - Room 1492
2:00 - 3:30 p.m.	Reviewers· Roundtable Discussion
3:30 - 4:30 p.m.	Question and Answer Session with Presenters
7:00 - 10:00 p.m.	Reception and Dinner at the Tivoli Restaurant

Wednesday, June 27, 1984

7:30 - 8:15 a.m.	Breakfast at the View Restaurant on the 14th floor.
8:30 - 9:20 a.m.	U.S. Geological Survey Research in Support of Multiwell Experiments Charles W. Spencer U.S. Geological Survey
9:20 - 10:10 a.m.	Seismic Investigation of the Multi-Well Experiment Site Craig A.Searls Sandia National Laboratories
10:10 - 10:25 a.m.	Break
10:25 - 11:15 a.m.	Crosswell Acoustic Imaging Project James N. Albright and Darrell A. Terry Los Alamos National Laboratories
11:15 a.m. - 12:05 p.m.	The Multiwell Experiment Core Program Allan R. Sattler Sandia National Laboratories
12:05 - 12:55 p.m.	Sedimentology of and Fractures in Mesaverde Rocks of the Multiwell Experiment Site and Environs John C. Lorenz Sandia National Laboratories
12:55 - 2:30 p.m.	Lunch
2:30 p.m.	Hospitality Suite is open - Room 1492
2:30 - 4:00 p.m.	Reviewers' Roundtable Discussion
4:00 - 5:00 p.m.	Question and Answer Session with Presenters

Thursday, June 28, 1984

7:30 -8:15 a.m.	Breakfast at the View Restaurant on the 14th floor.
8:30 - 9:20 a.m.	Log Interpretation Development Gerald .C. Kukal CER Corporation
9: 20 - 10:10 a.m,	Reservoir Analysis/Well Testing Paul Branagan CER Corporation
10:10 - 10:25 a.m.	Break
10:25 - 11:15 a.m.	Stimulation Design Norman R. Warpinski Sandia National Laboratories
11:15 a.m. - 12:05 p.m.	Fracture Diagnostics Dennis Engi Sandia National Laboratories
12:05 p.m. - 12:55 p.m.	Stimulation Analysis Norman R. Warpins/{i Sandia National Laboratories
12:55 - 2:30 p.m.	Lunch and Reviewers' Roundtable Discussion
2:30 p.m	Hospitality Suite is open - Room 1492
2:30 - 3:30 p.m.	Question and Answer Session with Presenters
3: 30. - 4: 30 p. m.	DOE Wrap-Up Session with Reviewers

NOTE: 30 MINUTES IS ALLOTTED FOR EACH PRESENTATION AND 20 MINUTES FOR QUESTIONS AND DISCUSSION.

RESEARCH PRESENTATIONS

The information in this section, summarized below was provided by the peer review session presenters. The materials are organized to folloW the agenda.

Presenter	Title and Description of Materials Provided
• Charles A. Komar Page 1-23	Unconventional Gas Recovery Program - Extraction Research. The view graphs are included.
• Karl H. Frohne Page 24-51	Western Gas Sands Subprogram. The view graphs are included.
• David A. Northrop Page 52-78	Multi-Well Experiment. The view graphs are included. Current Status of the Multiwell Experiment; Multiwell Experiment: A Field Laboratory for Tight Gas; MWX Stimulation Experiments. These three supporting documents are bound under separate cover as background information and wi 11 be provided at the review.
• Robert L.Mann Page 19-99	Multi-Well Experiment - An Operational Overview. The view graphs are included.
• Charles W. Spencer Page 100-123	USGS Research in Support of MWX. The complete report is included. Geologic Aspects of Tight Gas Reservoirs in the Rocky Mountain Region. This supporting document is bound under separate cover as background information and will be provided at the review.
• Craig A. Searls Page 124-141	Seismic Investigations of the Multi-Well Experiment Site. The view graphs are included.
• James N. Albright and Darrell A. Terry Page 142-174	Crosswell Acoustic Imaging Project. The complete report is included.

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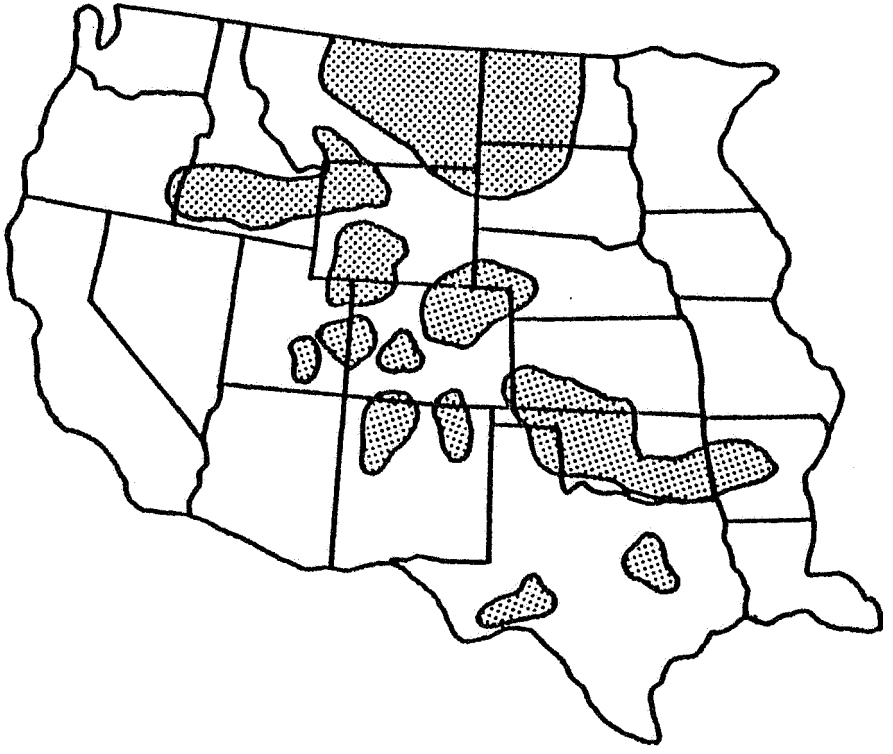
Presenter	TUle and Description of Materials Provided
• Allan R. Sattler Page 175-211	Multi-Well Experiment Core Program. The view graphs are included. The Multiwell Experiment Core Program. II. This supporting document is bound under separate cover as background information and will be provided at the review.
• John C. Lorenz Page 212-250	Studies of the Sedimentology and Natural Fractures of the Mesaverde Rocks at the MWX Site and Environs. The view graphs are inc1uded, Sedimentology of the Mesaverde Formation at Rifle Gap, Colorado and Implications for Gas Bearing Intervals in the SUbsurface; lateral Variability in the Corcoran and Cozzette Blanket Sandstones and Associated Mesaverde Rocks. Piceance Creek Basin. Northwestern Colorado; Reservoir Sedimentology in Mesaverde Rocks at the Multi-Well Experiment Site; Diagenesis and lUhification in Mesaverde Rocks at the MWX Site; Paludal Zone Sedimentology. These supporting documents are bound under separate cover as background information and will be provided at the review.
• Gerald C. Kukal Page 251-267	Improve Application of Conventional logs to Tight Sands. The complete report is included. Log Analysis in Low-PermeabilUy Gas Sand Sequences -- Correcting for Variable Unflushed Gas Saturation; A Systematic Approach for the Effective Log Analysis of Tight Gas Sands. These two supporting documents are bound under separate cover as background information and will be provided at the review.

Presenter	Title and Description of Materials Provided
• Paul T. Branagan Page 268-324	Well Testing Reservoir Evaluation. The view graphs are included.
• Norman R. Warpinski Page 325-378	MWX Stimulation Design; MWX Stimulation Analyses. The view graphs are included. Summary of Results of MWX Paludal Zone Phase I Stimulation; In-situ Stress Measurements at DOE's Multiwell Exper iment Site, Mesaverde Group. Rifle Colorado. These two supporting documents are bound under separate cover as background information and will be provided at the review.
• Dennis Eng; Page 379-399	Fracture Diagnostics. The view graphs are included. Fracture Diagnostics Results for the Multiwell Experiment's Paludal Zone Stimulation; Tight Gas Research and Development: The Industry Perspective; Mapping the Acid Stimulation in the Beowawe Geothermal Field Using Surface Electrical Potentials; 2.20 Integrated Real-Time Fracture Diagnostics Instrumentation System. These four documents are bound under separate cover as background information and will be provided at the review.

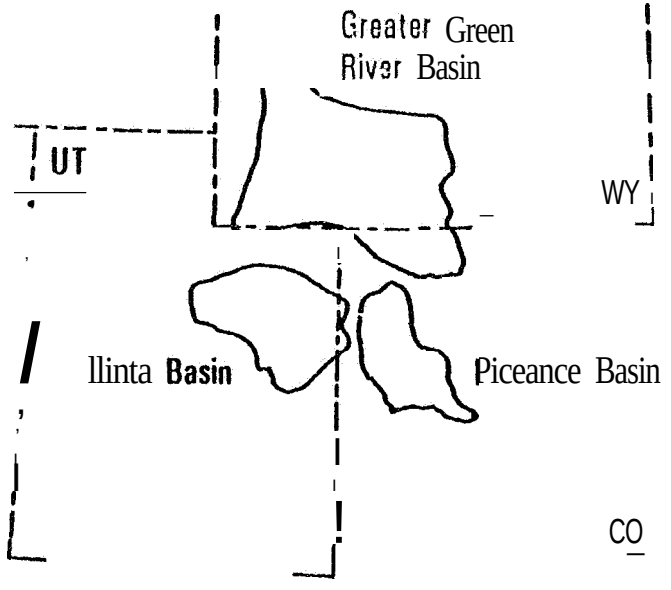
Western Gas Sands Subprogram



Unconventional Gas Recovery
Morgantown Energy Technology Center
U.S. Department of Energy

lenticular Tight Sands

Priority Basins

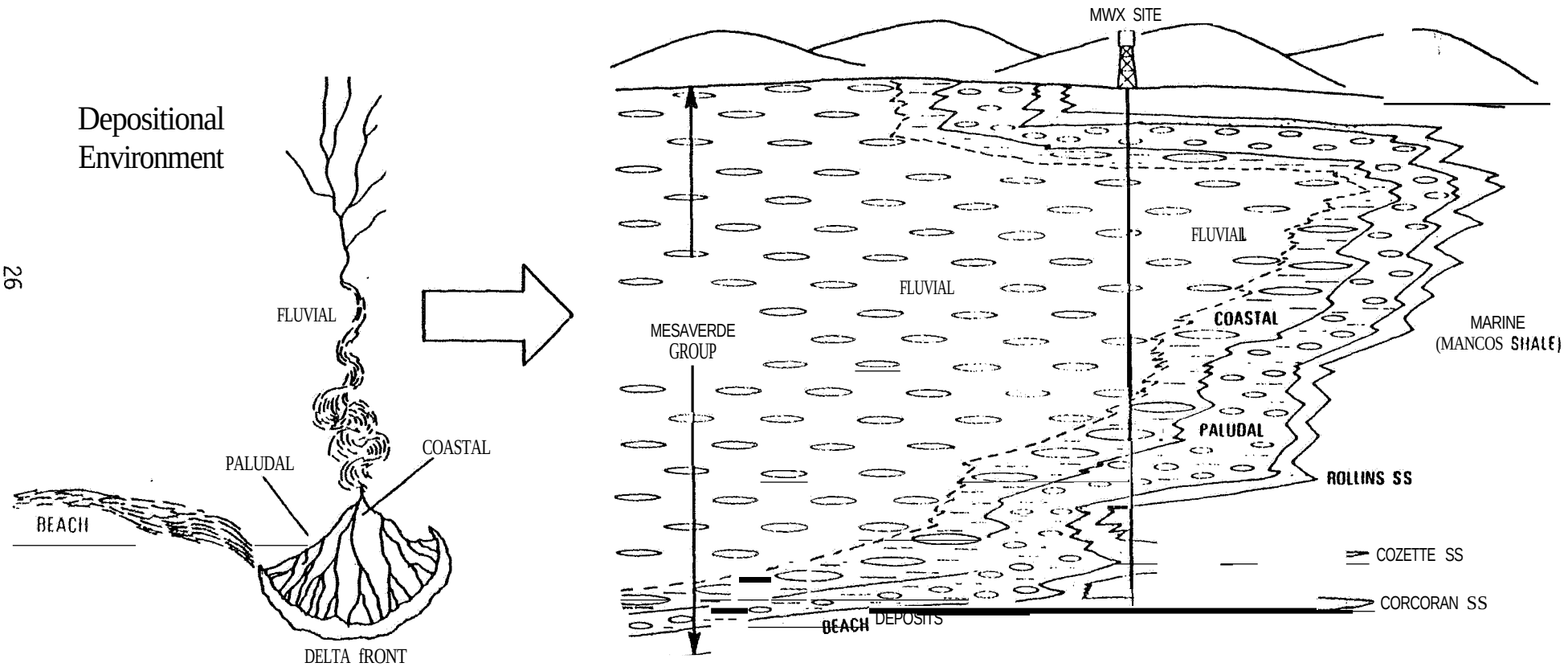


Targel Basin	Estimated Gip	Maximum Recoverable Gas·
Greater Green River	136	86
Piceance	49	33
Uinta	21	15
Total	206 TeF	134 TeF

(Source: NPC, 1980, Unconventional Gas Source)

Piceance Basin Geologic Setting

Mesaverde Group



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Western Gas Sands Major Technical Unknowns

- Extent of the resource
  - How great
  - Where
- lenticular reservoir characterization
  - Lens size and geometry
  - Orientation
  - Extent of natural fracturing
  - Extent of interconnection
- Reservoir performance
  - Reservoir properties
  - Detection and analysis
  - Well test design and analysis
  - Gas flow mechanics
- Stimulation technology
  - Control of geometry
  - Effective fluids and proppants
  - Propagation to remote lenses
  - Diagnostics for performance evaluation

Western Gas Sands Subprogram Goa's

- To ıeduce the unceııainty oıl the ıeseıvoır potentiaı
- To ·mpıove the extıaction ıechnology

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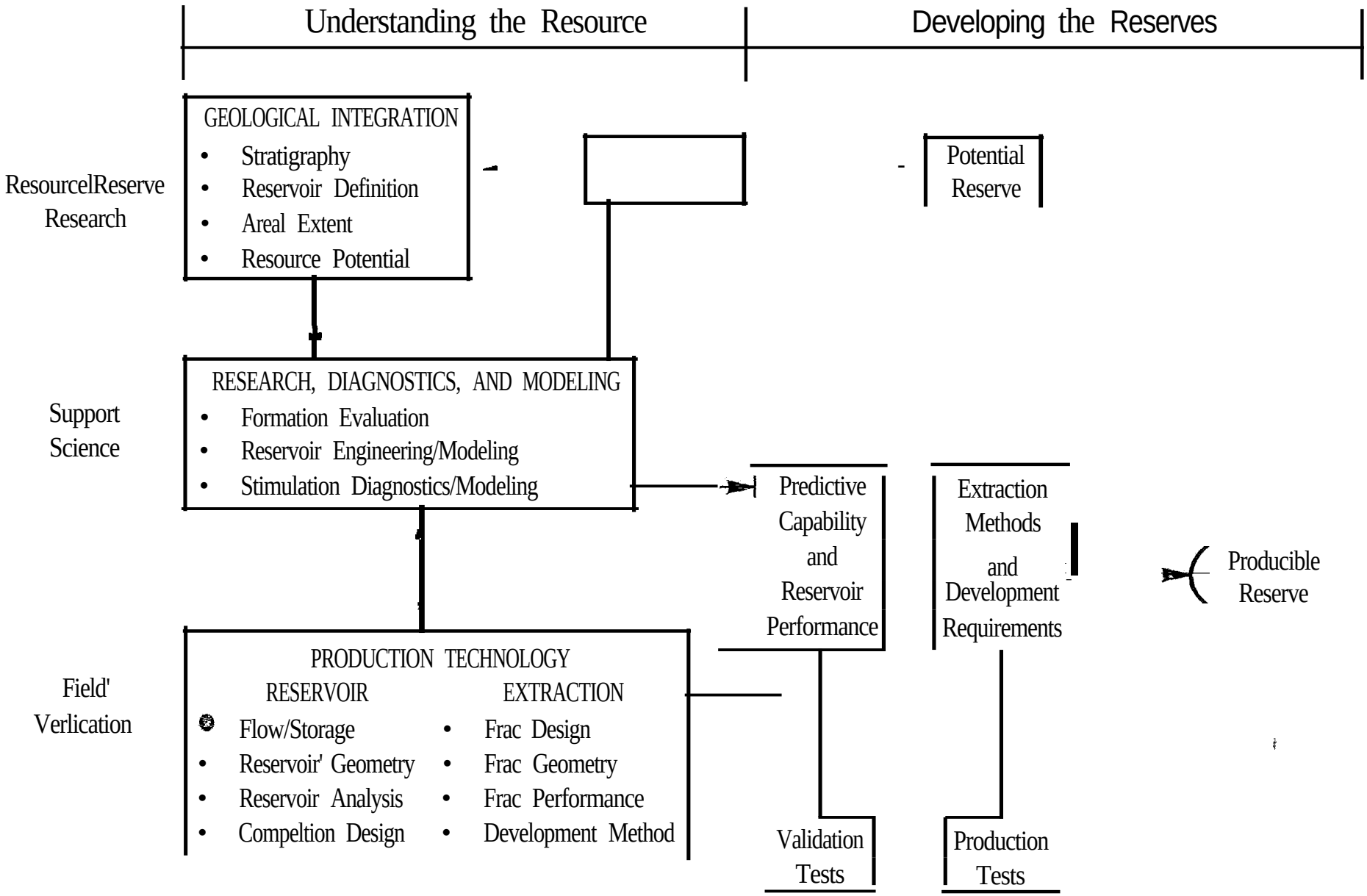
Current Approach To Western Gas Sands Research

- Improve understanding through generic research
- Set up a weU-instrumentedand well-characterized field laboratory to:
  - Determine the nature of the reservoirs and how to extract gas from them
  - Test the results of generic research in a realistic setting
- Extrapolate MWXsite results across the basin, then extend to other basins
- Establish the capability to predict production potential and stimulation performance
- Focus on Lenticular Sands

Western Gas Sana.Subpmqram logic



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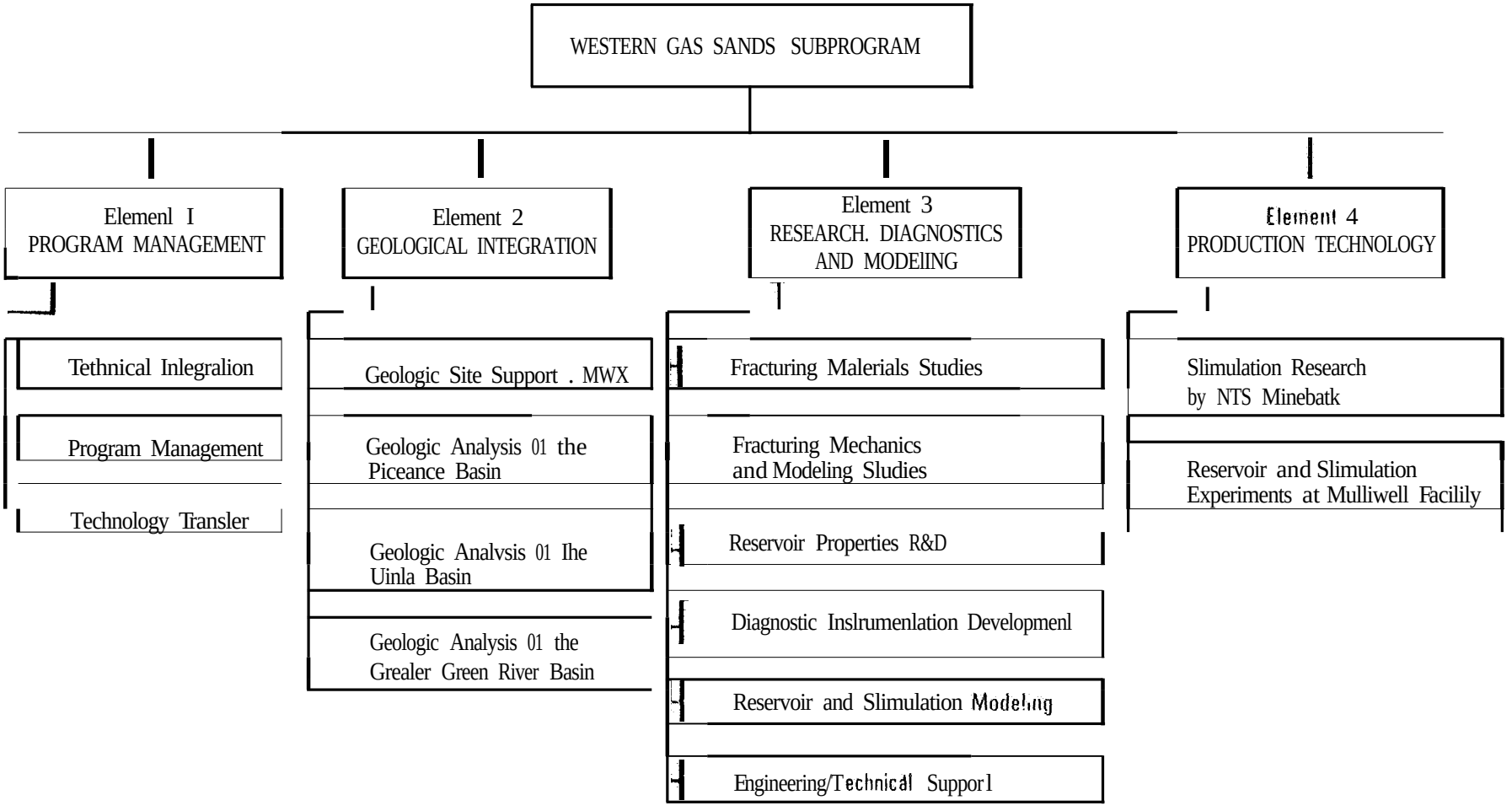
Activities in FY 84

- Investigate the mechanics of fluids, proppants, and formation interaction in gas recovery from tight sands
- Perform model development in support ofMWX data analyses
- Continue the geologic analysis and resource assessment of the Greater Green River Basin
- Conduct/inspect stimulation mineback research at NTS
- Conduct stimulation experiment in first Lenticular zone (MWX)
- Complete production testing of the Paludal (Lenticular) zone at the MWX site
- Evaluate first coastal zone to characterize reservoir properties for future stimulation testing
- Perform borehole/crosswell seismic R&D

Work Breakdown Structure



WGSS Funding Allocation FY84

Activity	Performer	Funds (X$1000)
Management		
Program Direction	FE/HO	150
Plan, Execute, Control, Integrate WGSS	METC	*
Multiwell Operations	BPO	*
Geologic Inlegration		
Greater Green River Basin Analysis	USGS	413
Research/Modeling		
Basic Reservoir Research	NMI	300
Engineering Support	SNLlCER	450
Modeling Support	EG&G	200
Integrated Stimulation Model	UT/ORU	500
Frac Height Code	ORU	35
Fracture Mechanics R&D	l1N1	400
Fracturing Materials R&D	NIPER	500
Cross Well Seismics R&D	lAN1	250
Production Technology		
Fracture Propagation Research (NTS)	SN1	302
Multiwell Experiment	SNLlCER	4500
Reservoir Characterization		
Stimulation Performance Analysis		
	Total Budget	$8,000,000

*Program Direction Funds

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Geological Integration FY·84 Research

Activity	Performer
Geologic Basin Analysis. Greater Green River Basin	USGS
Uinta Basin Generic Research	
Multi-well Experiment Support • Core Analysis • Well logging • Rock Engineering Properties • Reservoir Properties	
Generic Research • 3-D Seismic Studies • Sedementology • Source rock/maturation studies	

Geologic Integration . Selected Recent Accomplishments

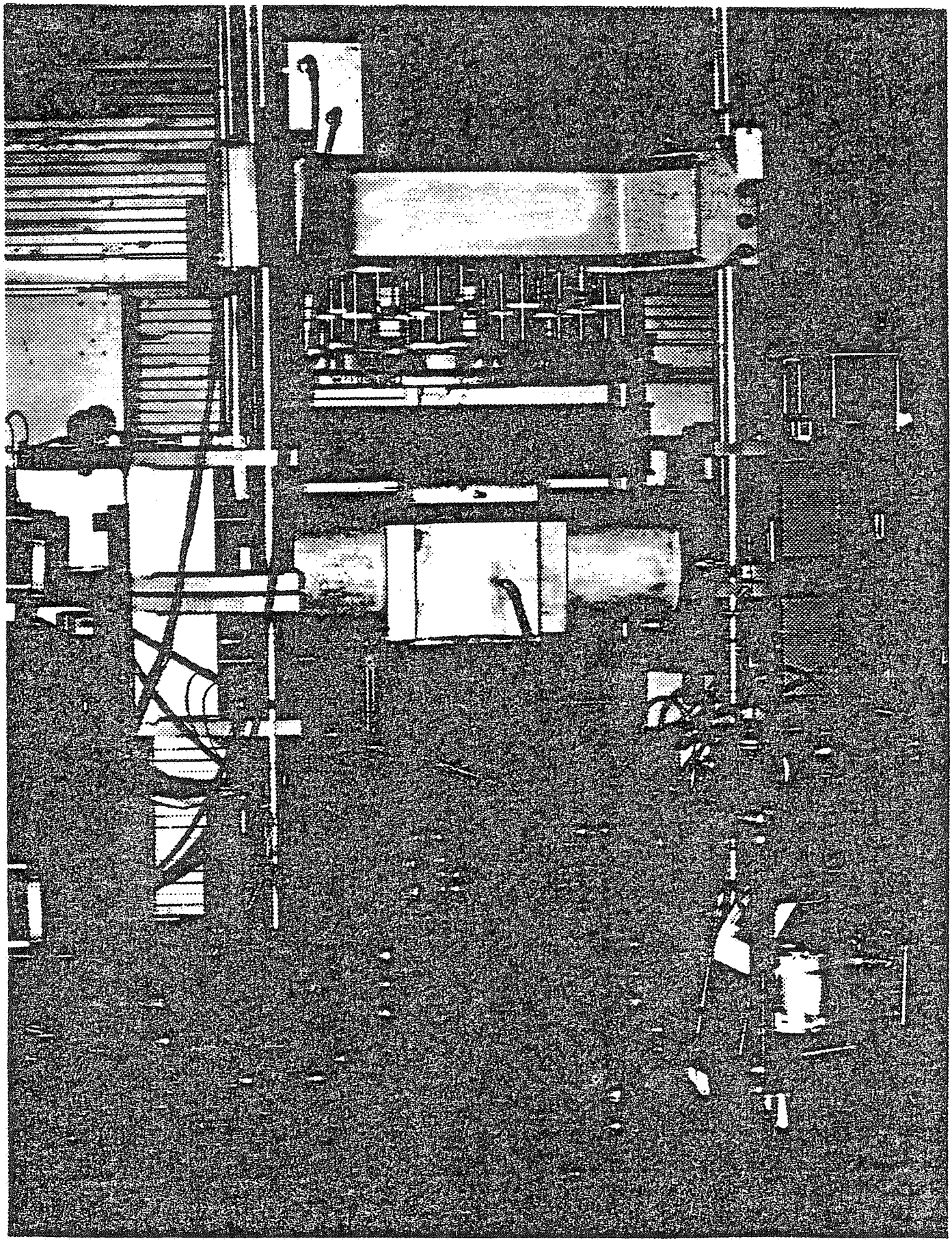
- Performed comprehensive geologic analysis of the Piceance Basin
  - Stratigraphy, sedimentology, mineralogy
  - Reservoir characterization
  - Source rock/maturation studies
  - Mechanical rock properties
  - Integrated geologic basin medel

Research, Diagnostics, and Modeling FY 84 Research

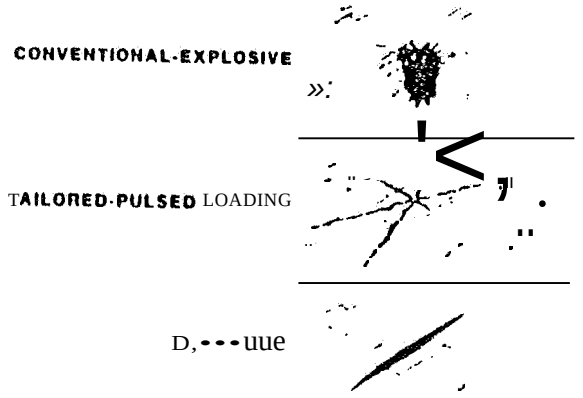
Activity	Performer
• Reservoir properties R&D - Matrix porosity/perm studies	New Mexico Institute
• Fracturing materials R&D - Fluid,proppant, & damage studies	NIPER
• Fracturing mechanics studies - laboratory/Modeling R&D	lawrence livermoreNl
• Geophysics R&D - Crosswell seismics	los Alamos Nl
• Predictive models	
- Reservoir simulator	Univ. of Oklahoma
- Stimulation models	Univ. of Tulsa
- Fracture geometry model	Oral Robert Univ.
- Model application & support	METC/EG&G
• Western Gas Sands Technical Support - Reservoir test analysis - log interpretation	CER Corp.

Research, Diagnostics, And Modeling — Selected Recent Accomplishments

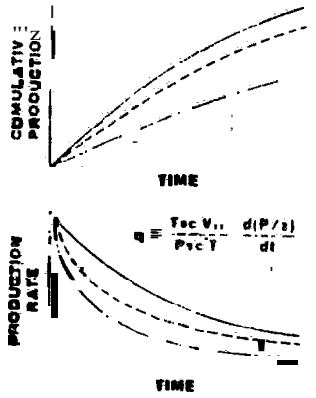
- Development of advanced proppants for severe stress application in Tight Sands
- Development of an advanced logging concept (NMR prototype) for saturation measurement in Tight Sands
- Development of a 2-phase, 2-porosity reservoir model



PREDICTIVE CAPABILITIES

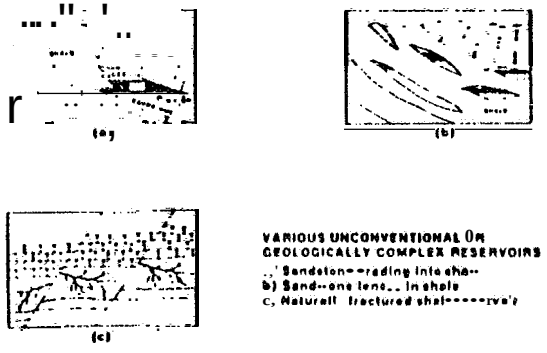


STIMULATION

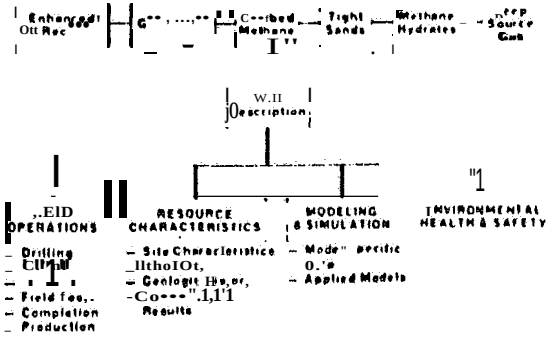


RESERVOIR PERFORMANCE

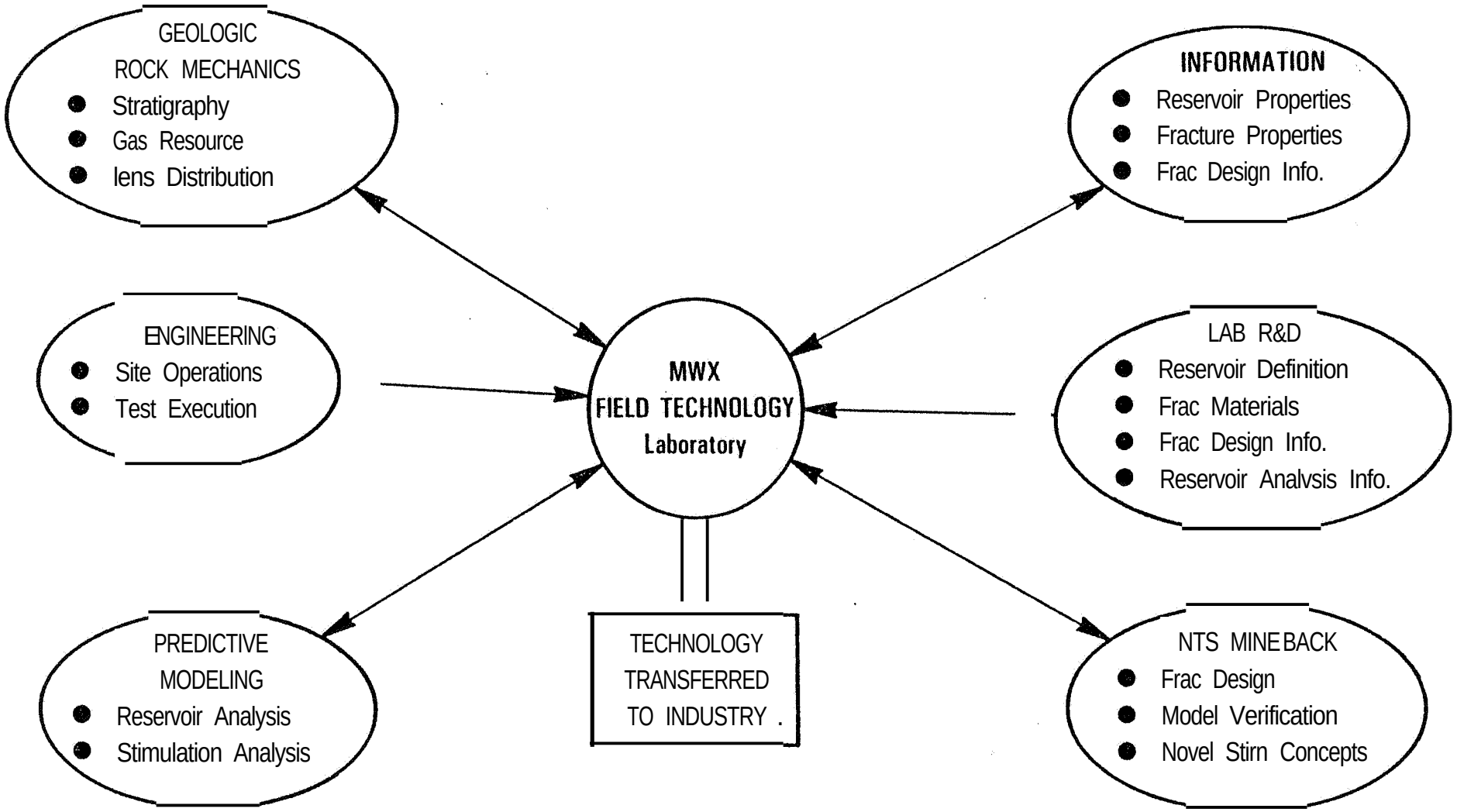
GEOLOGIC ANALVSIS



DATA BASES



MultiweU Experiment Strategy



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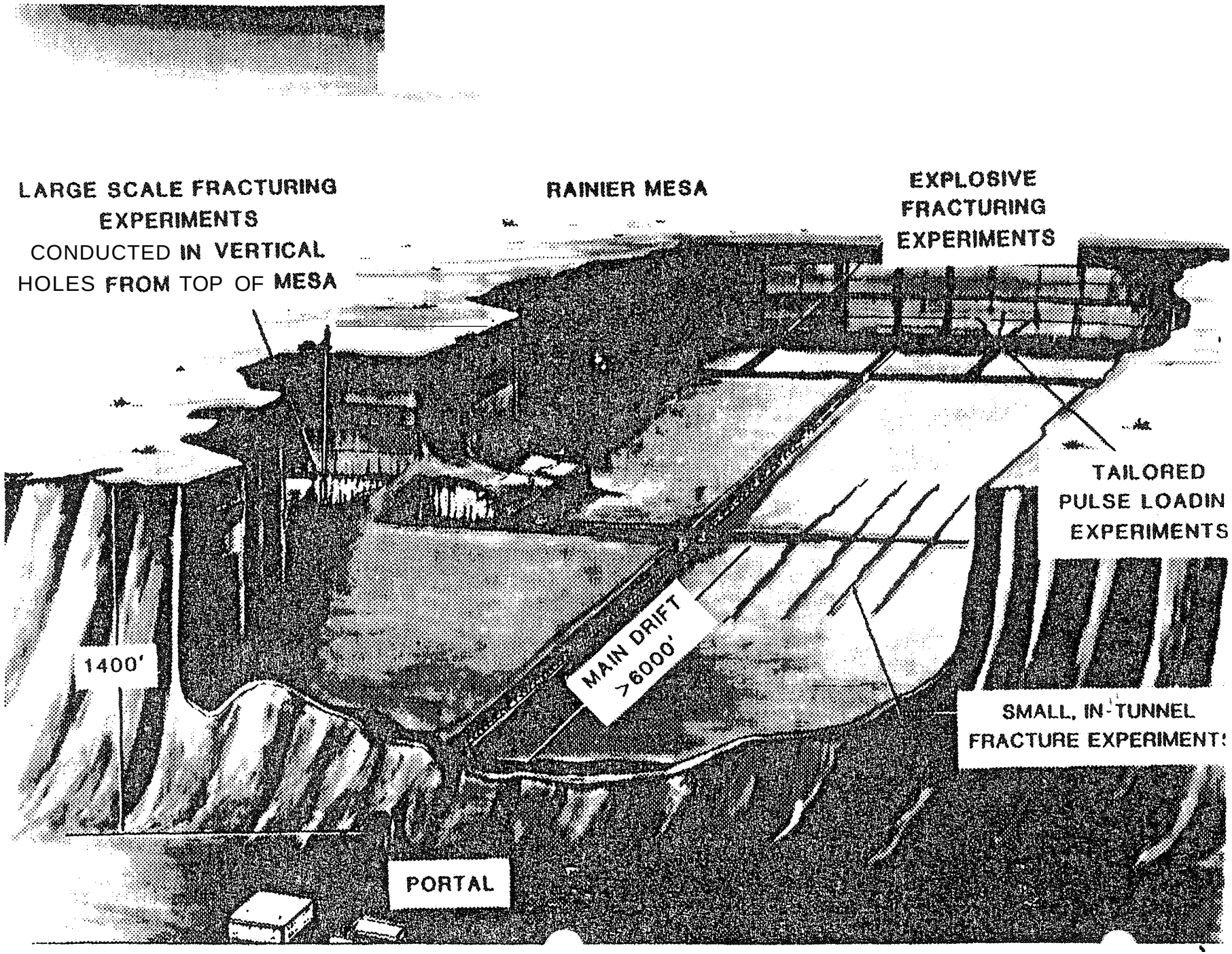
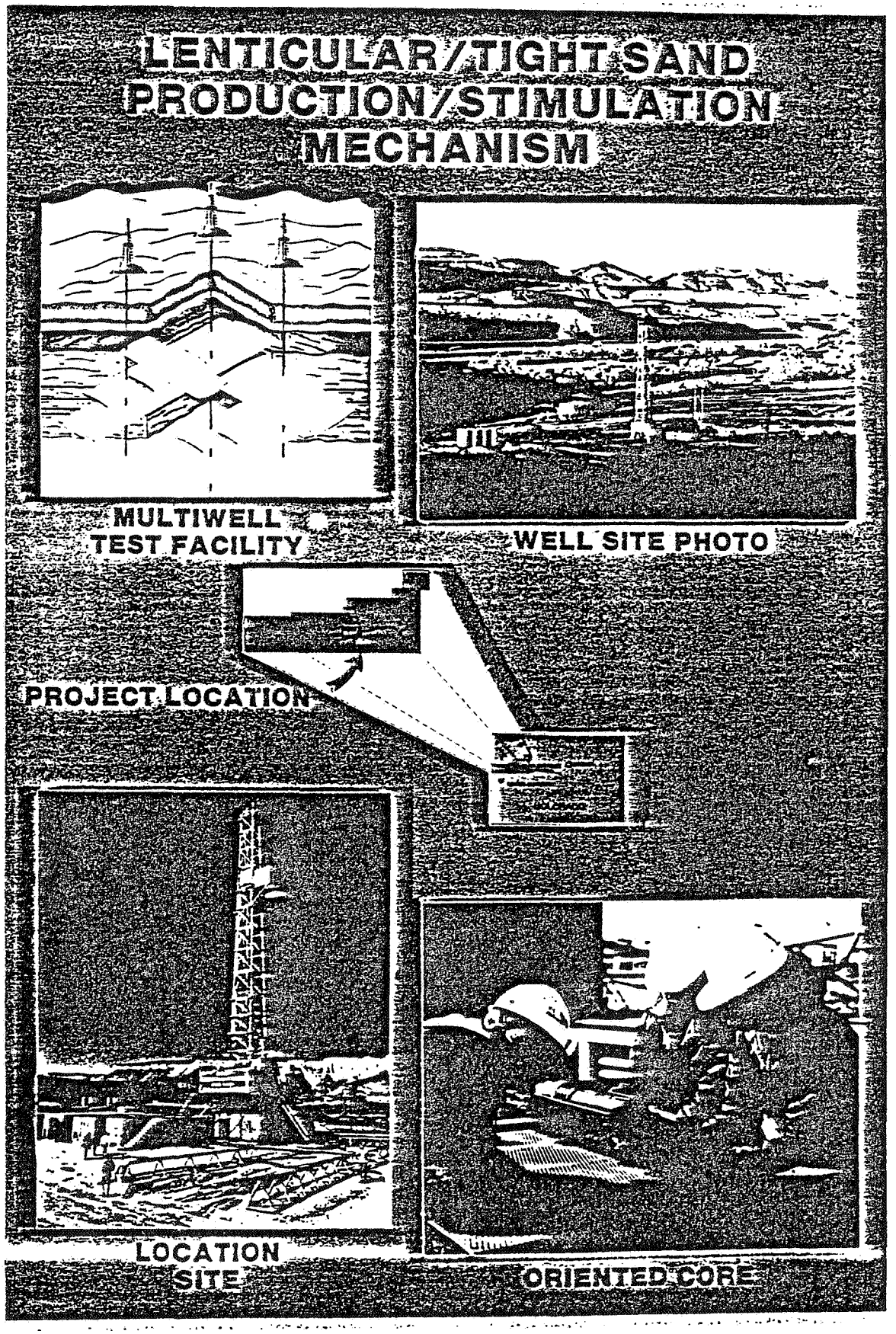
Production Technology FY84 Research

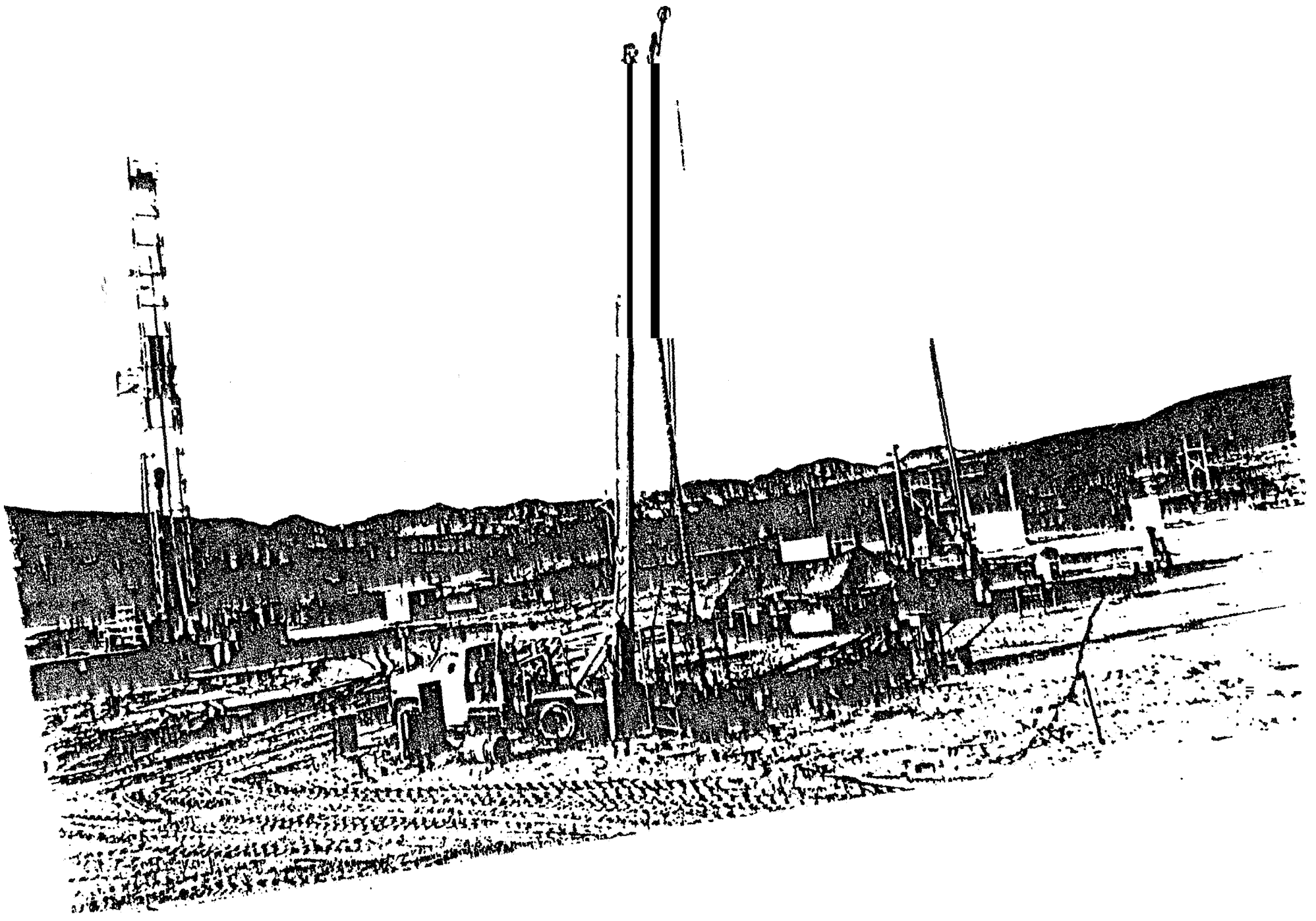
Activity	Performer
MultiweUExperiment	SNL/CER
• Stimulation Test and Performance Evaluation of Paludal lenses	
• Reservoir Baseline Evaluation of lower Coastal lenses	
NTS (Mineback) Stimulation Research	SNt
• Instrument and Execute Hydraulic Fracture with Proppant Experiment	

Production Technology . Selected Recent Accomplishments

- Completed installation phase of Mulliwell Field lab with drilling of 3rd well
- Evaluated reservoir potential of Corcoran/Collette blanket sands
- Evaluated baseline performance of Paludal (lenticular) target lone
- Completed Phase I minifracs of Paludal target zenes


LARGE SCALE FRACTURING EXPERIMENTS CONDUCTED IN VERTICAL HOLES FROM TOP OF MESA
RAINIER MESA
EXPLOSIVE FRACTURING EXPERIMENTS
TAILORED PULSE LOADIN EXPERIMENTS
1400'
MAIN DRIFT >6000'
SMALL, IN-TUNNEL FRACTURE EXPERIMENTS
PORTAL

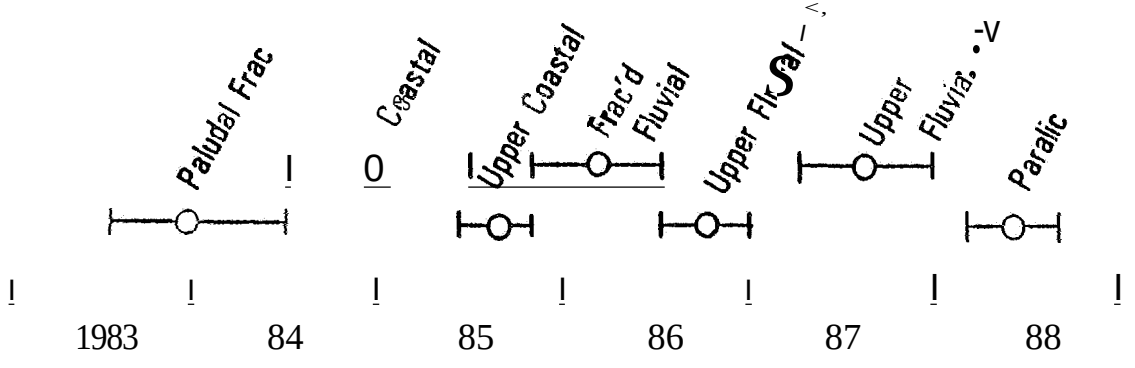

LENTICULAR/TIGHT SAND
PRODUCTION/STIMULATION
MECHANISM
MULTIWELL
TEST FACILITY
WELL SITE PHOTO
PROJECT LOCATION
LOCATION
SITE
ORIENTED CORE



MWX Test Cycle

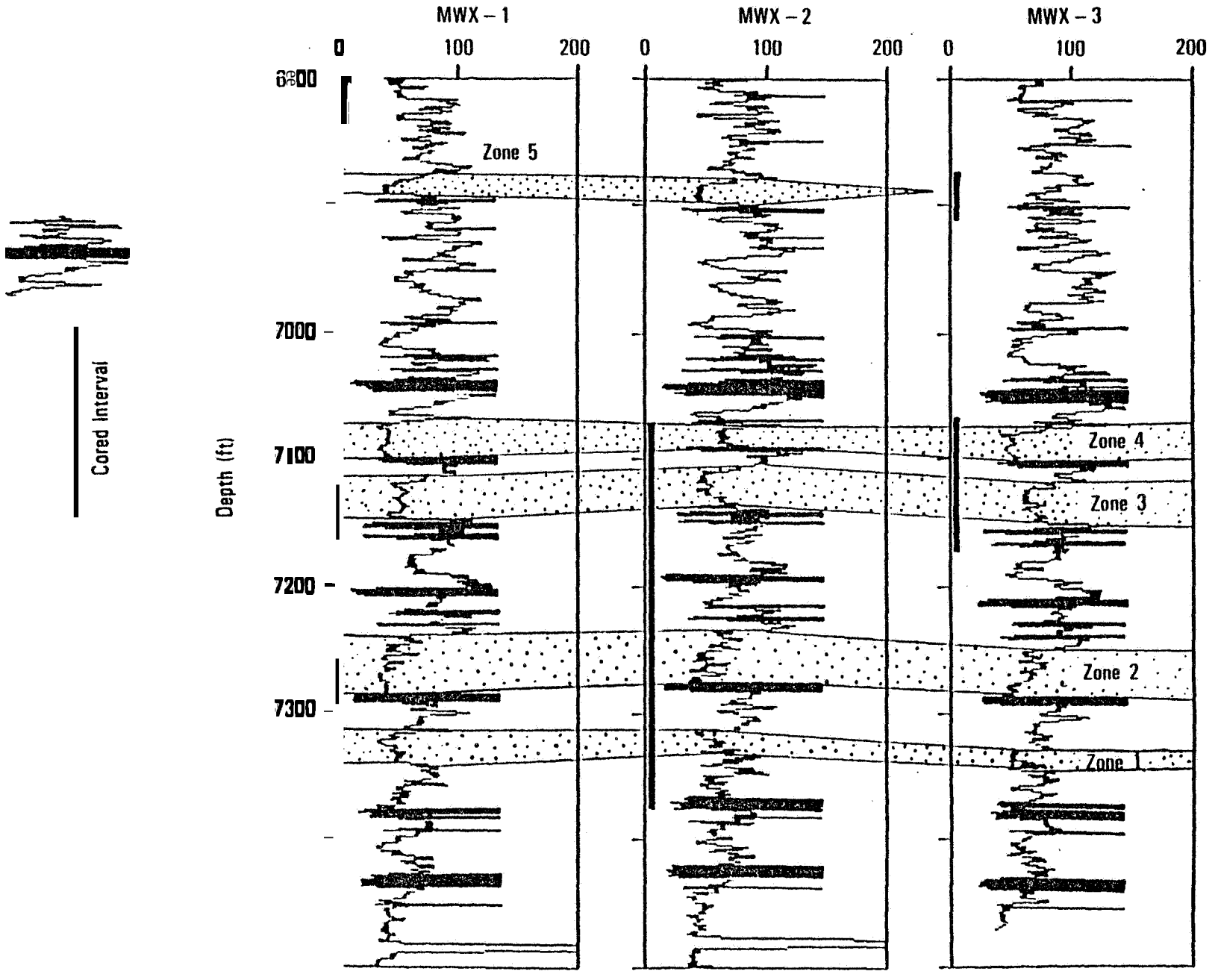
(3 Cycles in 2 Years)

- Select test zone from core/loganalysis
- Stress tests for frac design
- Well tests to baseline target reservoir potential
- lab/modelinginput to frac design
- Stimulation experiment with full diagnostics for frac geometry
- Post· frac well tests to evaluate stimulation performance

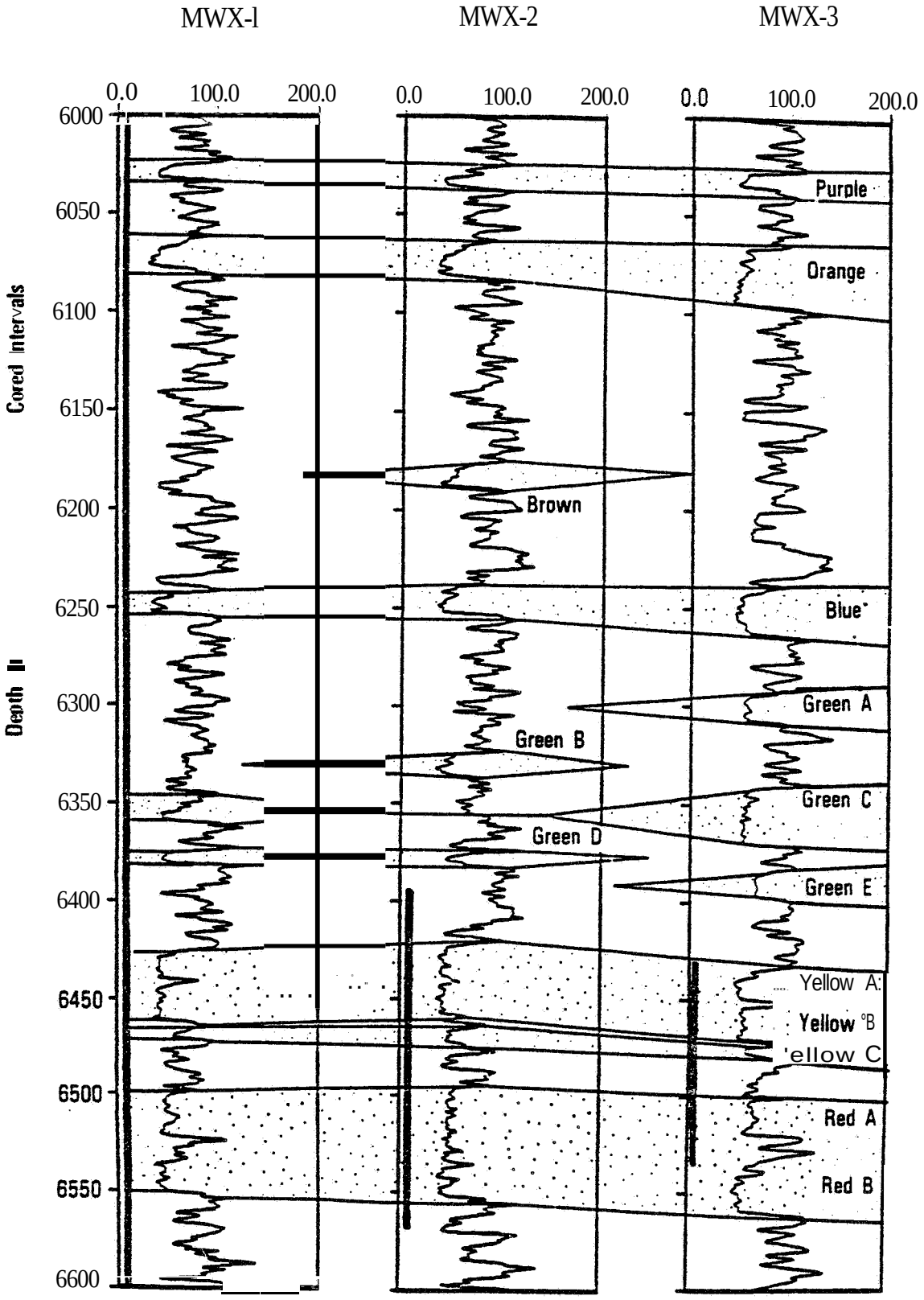


Test Schedule

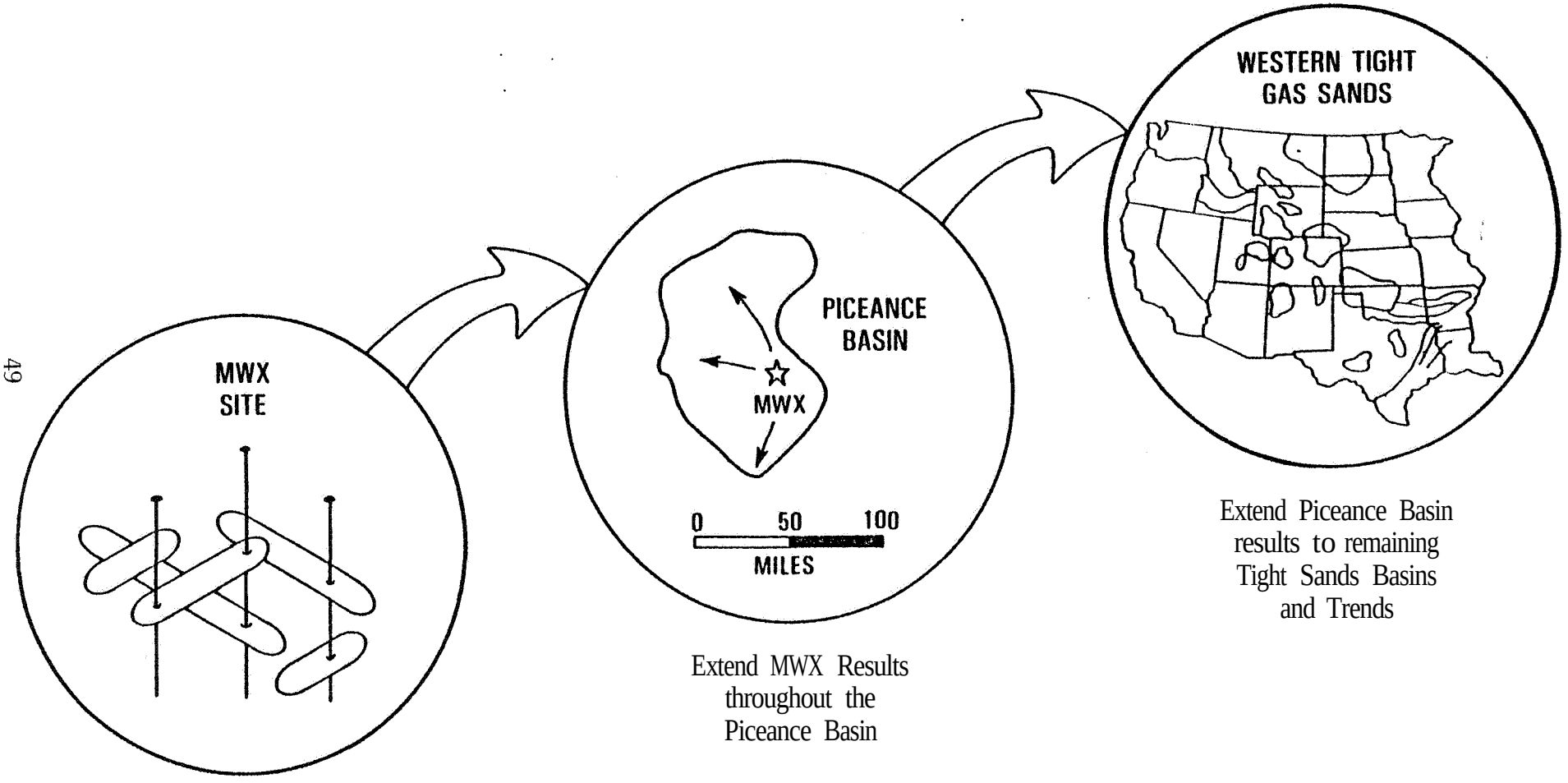
Paludal Zone Reservoirs



Coastal Zone Reservoirs



Technology Extrapolation Strategy



Extensive Site-Specific research at a fully characterized field test facility

Extend MWX Results throughout the Piceance Basin

Extend Piceance Basin results to remaining Tight Sands Basins and Trends

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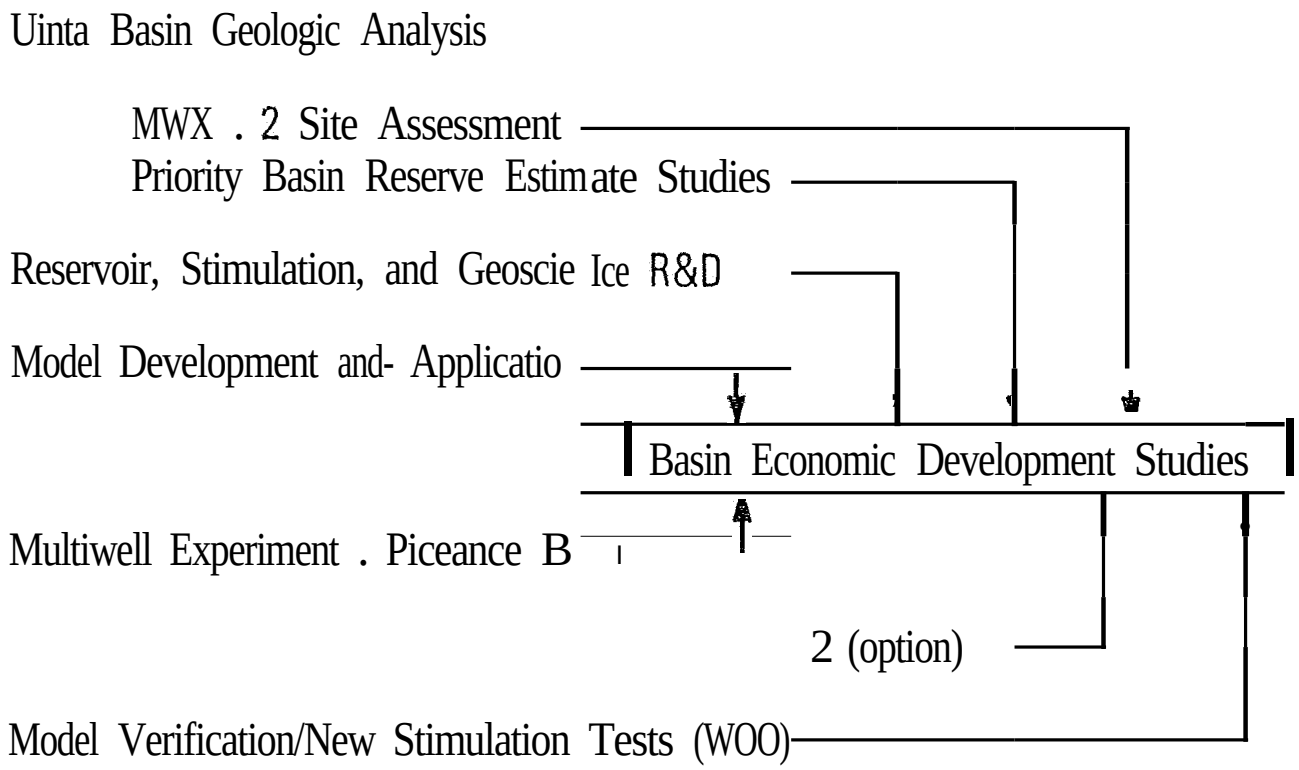
Western Gas Sands FYB5 Activities Plan

Activity	Performer	Funds
Program Direction	HOIFE	$ 287K
Greater Green River Basin Analysis	USGS.	313
ModelinglDatabase Support	METC/EG&G	350
Basic Reservoir Research	NMI	70
WGSS Technical Support	SNL/CER	330
Multiwell Experiment	SNl/CER	3400
	Total FY85 funds	$4750K
Crosswell Seismic R&D	lANl	$ 165K*
Fracture Mechanics R&D	LLNl	400*
Stimulation R&D (NTS)	SNL	400·
Technical Support	SNl/CER	70·
	Total WGSS Reserve	$1035K

·WGSS Prior Year Reserve Funds

Western Gas Sands Major Thrusts . FY86 and Beyond



PROJECT

TITLE:	MULTI-WELL EXPERIMEm
ORGANIZATIONS:	SANDIA NATIONAL LABORATORIESI CER CORPORATION
PRINCIPAL INVESTIGATORS:	VARIOUS
PERIOD OF PERFORMANCE:	CONTINUING PROGRAM (AUGUST 1979 - DECEMBER 1988)
CONTRACT FUNDING:	$25/545/000 THROUGH FY84

PRESENTATION

OVERVIEW OF THE MULTI-WELL EXPERIMENT

DAVID A. NORTHROP

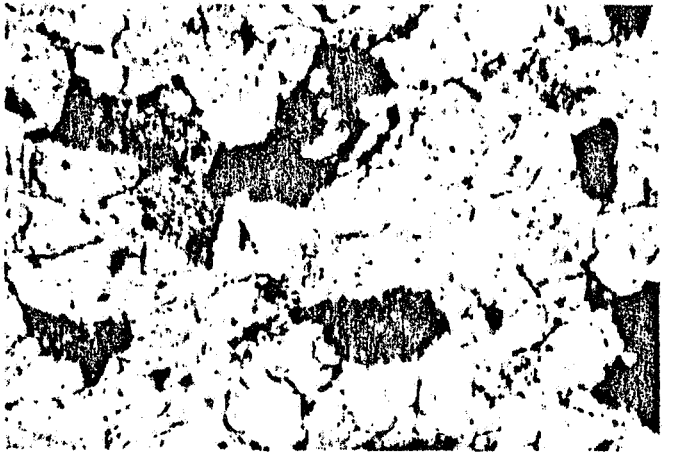
SANDIA NATIONAL LABORATORIES

PRESENTATION OUTLINE

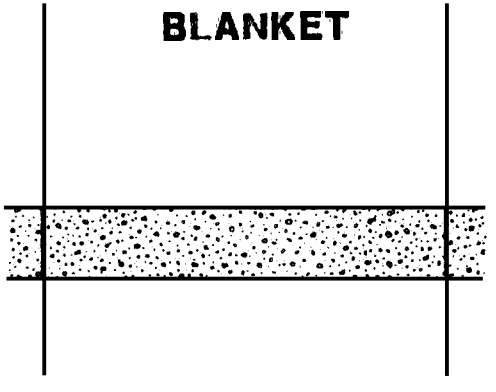
- RESOURCE
- RATIONALE
- DESCRIPTION
- HISTORY/ACCOMPLISHMENTS
- FUTURE
- ADMINISTRATIVE

CONVENTIONAL

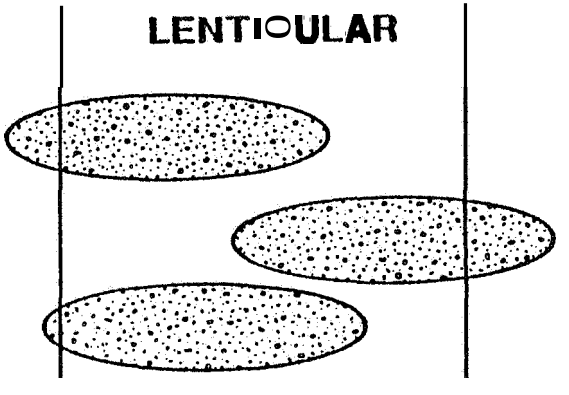
TIGHT

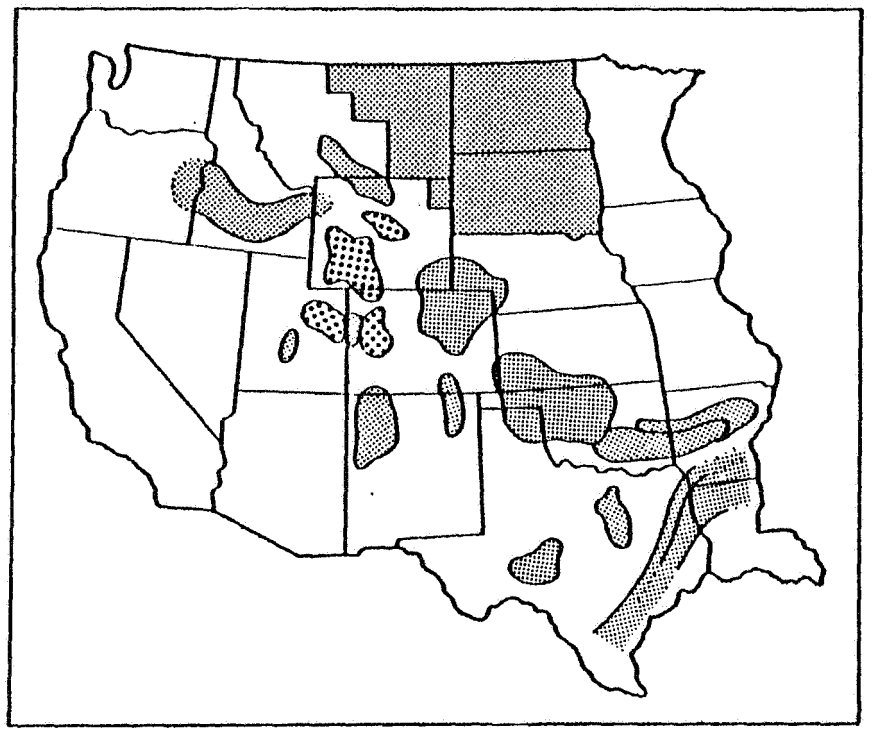


BLANKET



LENTICULAR





GAS IN PLACE

LENTICULAR	192.0
BLANKET	23.9
COMBINED	23.3
TOTAL	239.3 TCF

(SOURCE: NPC, 1980)

MOTIVATION:

PAST FIELD EXPERIMENTS AND TESTS HAVE PROVIDED INSUFFICIENT INFORMATION TO UNLOCK THIS RESOURCE

FRACTURINGRESULTS:MHF-3EXPERIMENT

	HYDRAULIC FRACTURE			
	1	2	3	4
FLUID VOLUME (gal)	117,500	285,000	344,000	228,000
SAND PROPPANT (lbs)	400,000	880,000	809,000	448,000
FRAC INTERVAL (ft)	40	80	112	20
DESIGN FRAC LENGTH (tt)	840	920	860	1648
POST-FRAC LENGTH (It) (PRODUCTION MATCH)	110-170	150	100	20-30
GAS FLOW, BEFORE (MCFID)	60	57	43	55
GAS FLOW, AFTER (MCFID)	61	137	160	69

POSSIBLE EXPLANAIiONS FOR POOR RESULTS:

- FRACTURE OUT OF ZONE - VERTICAL NOT LATERAL FRACTURE EXTENSION
- REMOTE LENSES NOT INTERSECTED - LENS SMALLER THAN BELIEVED
- POOR FRACTURE CONDUCTIVITY - SHALES NOT PROPPED
- CURRENT LOGS CAN'T IDENTIFY GAS-BEARING SANDS AND GAS-IN-PLACE

CHARACTERISTICS OF PAST FIELD EXPERIMENTS:

- PRODUCTION-ORIENTED PLANS, SCHEDULES AND BUDGETS
- WELL SPACING $\geq$ 1 MILE $\gg$ LENS DIMENSIONS
- NO CORE EXISTS FOR FRACTURED INTERVALS
- LIMITED, IF ANY, FRACTURE DIAGNOSTICS
- LIMITED DATA FOR ANALYSIS: GAS PRODUCTION AND LOGS

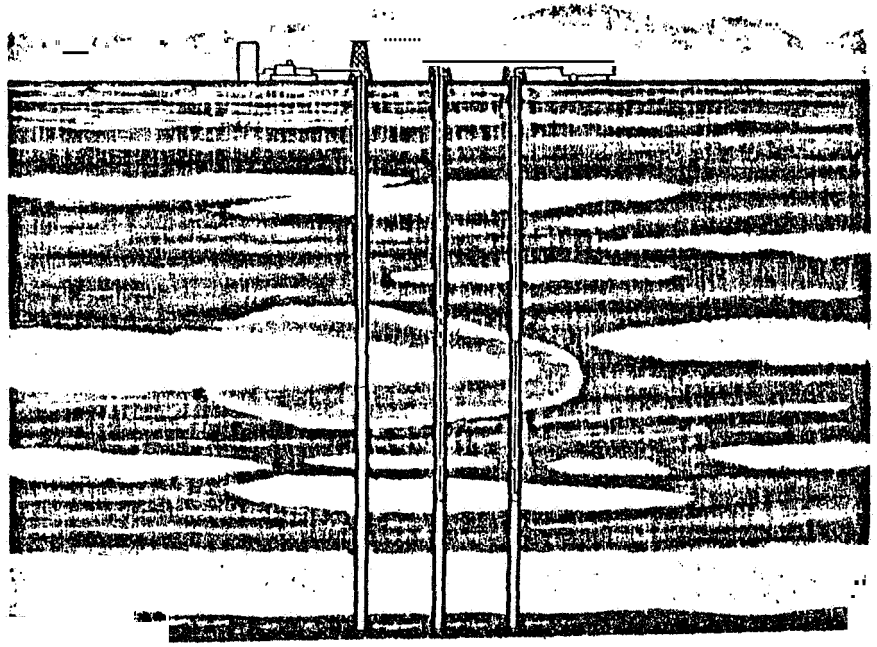
MULTI-WELL EXPERIMENT

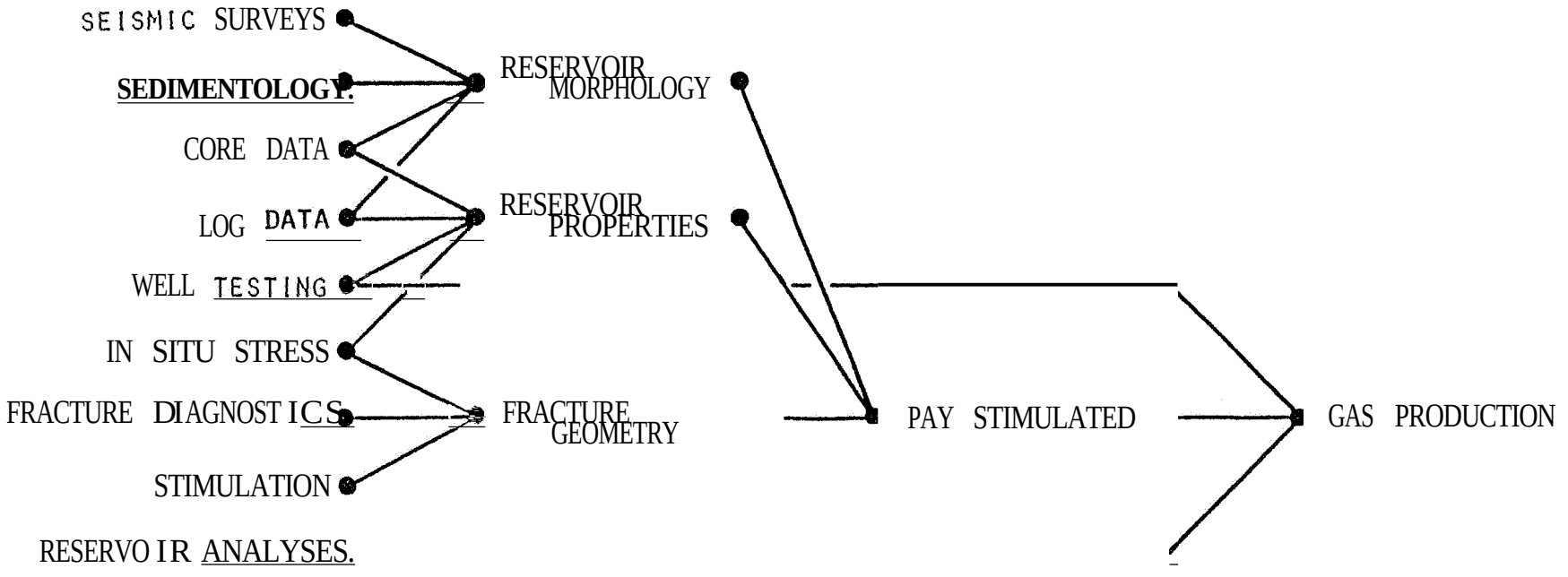
AFIELD LABORATORY FOR TIGHT GAS SANDS

- ITS OBJECTIVE IS TO INCREASE PRODUCTION FROM LENTICULAR TIGHT GAS RESERVOIRS THROUGH GEOLOGIC CHARACTERIZATION AND TECHNOLOGY DEVELOPMENT

MULTI·WELL EXPERIMENT

- CLOSE-SPACED WELLS WITH FULL MESAVERDE CORE
- COMPREHENSIVE CORE ANALYSIS. LOGGING AND WELL TESTING PROGRAMS
- VARIED STIMULATION EXPERIMENTS
- GEOPHYSICAL, FRACTURE DIAGNOSTICS, AND IN SITU STRESS MEASUREMENTS
- ANALYSES AND EVALUATION FOR IMPROVED MODELS AND UNDERSTANDING




SEISMIC SURVEYS
SEDIMENTOLOGY.
CORE DATA
LOG DATA
WELL TESTING
IN SITU STRESS
FRACTURE DIAGNOSTICS
STIMULATION
RESERVOIR ANALYSES.
RESERVOIR MORPHOLOGY
RESERVOIR PROPERTIES
FRACTURE GEOMETRY
PAY STIMULATED
GAS PRODUCTION

MULTI-WELL EXPERIMENT - SPECIFIC GOALS

-DETERMINE THE SIZE} SHAPE} ORIENTATION AND DISTRIBUTION OF LENTICULAR SANDS

-DETERMINE IN SITU RESERVOIR PROPERTIES AND QUANTIFY THEIR VARIATIONS WITHIN A LENS AND BETWEEN LENSES

- IMPROVE RELIABILITY AND ACCURACY OF LOGS IN TIGHT GAS SANDS

• DETERMINE THE EFFECTS OF EARTH STRESSES UPON STIMULATION AND GAS PRODUCTION

• CONDUCT STIMULATION EXPERIMENTS TO EVALUATE TECHNOLOGY AND ANSWER KEY QUESTIONS

• PERFORM ANALYSES AND EVALUATIONS TO ASSESS VIABILITY OF GAS PRODUCTION FROM LENTICULAR TIGHT GAS RESERVOIRS

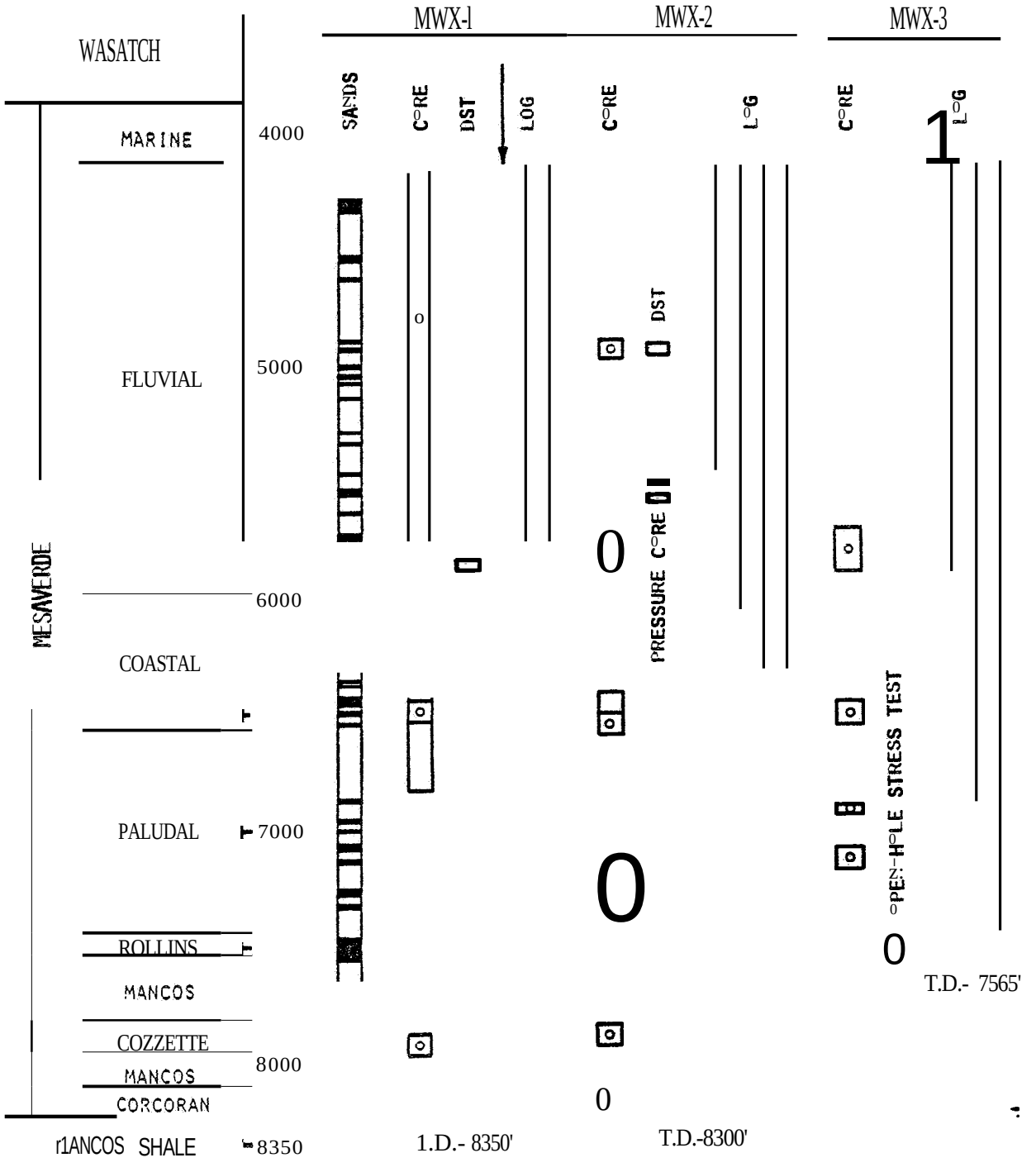
MWX PERSONNEL

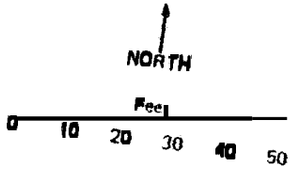
	ACTIVITY	PRINCIPAL INVESTIGATOR
SANDIA	MANAGEMENT	NORTHROP) SATTLER
	CORE ANALYSIS) CORRELATIONS	SATTLER
	GEOLOGY) NATURAL FRACTURES	LORENZ
	STIMULATION, STRESS	WARPINSKI
	FRACTURE DIAGNOSTICS	ENGI
	GEOPHYSICS	SEARLS
CER	MANAGEMENT	MANN
	SITE OPERATIONS	COATS" MATBIS
	TEST TRAILER	WILMER
	RESER. TEST AND ANALYSIS	BRANAGAN
	LOGGING) CORRELATIONS	KUKAL
	WGSS SUPPORT	VARIOUS

SNAPSHOT HISTORICAL SUMMARY--MULTI-WELL EXPERIMENT

MAY 1979	FIRST PLANNING MEETING
JUL 1979	FIRST TECHNICAL REVIEW PANEL 'MEETING
JAN 1980	MAJOR OVERALL MWX PLANNING/NETWORK SESSION
1980	SITE SEARCH AND NEGOTIATIONS
JAN 1981	SITE AGREEMENT SIGNED WITH SUPERIOR
FEB-MAY 1981	LOCAL (COLORADO) PROBLEMS; SITE MOVED
JUL 1981	REVISED SITE AGREEMENT (S YEARS)
AUG-SEPT 1981	SITE CONSTRUCTION
OCT-DEC 1981	MWX-1
JAN-MAR 1982	MWX-2
APR-DEC 1982	CORCORAN-COZZETTE TESTING
JAN-MAR 1983	SITE SHUTDOWN
APR-Nov 1983	PALUDAL TESTING
JUN-AuG 1983	MWX-3
SEP 1983	SITE AGREEMENT EXTENDED THROUGH JULY 1988
DEC 1983	PALUDAL STIMULATION EXPERIMENT (PHASE 1)
JAN-MAR 1984	SITE SHUTDOWN
APR--JuN 1984	PALUDAL STIMULATION EXPERIMENT (PHASE 2)

)


MWX-1
MWX-2
MWX-3
WASATCH
MARINE
FLUVIAL
COASTAL
PALUDAL
ROLLINS
MANCOS
COZZETTE
MANCOS
CORCORAN
MESAVERDE
MANCOS SHALE
4000
5000
6000
7000
8000
8350
SANDS
CORE
DST
LOG
CORE
DST
PRESSURE CORE
LOG
CORE
OPEN-HOLE STRESS TEST
LOG
T.D.- 7565'
T.D.-8300'
T.D.- 8350'



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MULTI-WELL EXPERIMENT ACCOMPLISHMENTS

• THREE WELLS DRILLED	7550-8350' DEEP; 115-215' SEPARATIONS
• COMPREHENSIVE CORE PROGRAM	4150' OF CORE; 20+ PARTICIPANTS
• EXTENSIVE LOGGING PROGRAM	OIL- AND WATER-BASED MUDS; INCLUDES NEW TECHNIQUES
• LENTICULAR SANDS CONTINUITY	QUANTIFIED PROPERTY VARIATIONS
• FRACTURE AZIMUTH PREDICTION	SEVERAL METHODS; CONFIRMED
• DEPOSITIONAL ENVIRONMENTS DEFINED	MESAVERDE RESERVOIR MORPHOLOGIES
• SEISMIC SURVEYS CONDUCTED	3D SURFACE; VSP(2); CRoss-BoREHOLE
• NATURAL FRACTURE EFFECTS	CORE} LOG} WELL TESTJ GEOLOGIC DATA; STRESS HISTORY
• WELL TESTING	INCLUDES INTERFERENCE; CORCORAN} COZZETTE} PALUDAL
• IN SITU STRESS MEASUREMENTS	CASED AND OPEN HOLE; FRAC CONTAINMENT
• PALUDAL STIMULATION EXPERIMENT	Two PHASES; DEC. 1983 AND MAY 198
• FRACTURE DIAGNOSTICS	BOREHOLE SEISMIC MAPPING; FRAC AZIMUTH AND HEIGHT

STIMULATION EXPERIMENT METHODOLOGY

- CORE, LOG, GEOLOGIC CHARACTERIZATION
- IN SITU STRESS MEASUREMENTS
- WELL TESTING
- COMPILE DATA SET
- SPECIFY OBJECTIVES
- STIMULATION DESIGN
- CONDUCT STIMULATION
- POST-FRAC TESTING
- ANALYSIS

STIMULATION EXPERIMENT GOALS

- DETERMINE HYDRAULIC FRACTURE GEOMETRY IN RELATION TO LENS ORIENTATION AND EXTENT IN ORDER TO SEPARATE FACTORS AFFECTING GAS PRODUCTION

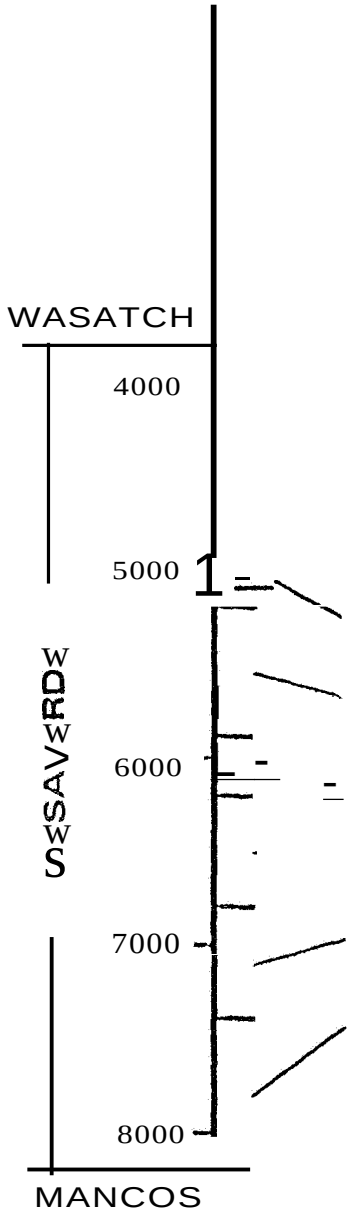
- DETERMINE IF LENSES NOT IN CONTACT WITH THE WELLBORE CAN BE INTERSECTED AND PRODUCED

- DETERMINE IF A SERIES OF LENSES IN CONTACT WITH THE WELLBORE CAN BE EFFICIENTLY PRODUCED

- EVALUATE GEOLOGICIRESERVOIR FACTORS
  (E.G., WATER SATURATION; EARTH STRESS; ROCK TYPE; ETC.)

- EVALUATE STIMULATION FACTORS
  (E.G., FLUID TYPE; PROPPANT TYPE OR CONCENTRATION" FRAC RATE, ETC.)

- EVALUATE NEW STIMULATION TECHNIQUES" AS AVAILABLE



MWX STINULATION EXPERIMENTS

TITLE		DATES	FIELD TIME (MO)
PARALIC	HIGH S_w, K	3/88 - 6/88	4
UPPER FLUVIAL	LENTICULAR SERIES	3/87 - 12/87	10
UPPER FLUVIAL	REMOTE LENS	9/86 - 12/86	4
LOWER FLUVIAL	NATURAL FRACTURES	10/85 - 8/86*	9
UPPER COASTAL	REMOTE LENS	6/85 - 9/85	4
COASTAL	LENTICULAR SANDS	7/84 - 5/85*	9
PALUDAL	COMPLEX GEOLOGY	9/83 - 6/84*	7
BLANKET			

* INCLUDES 3-MONTH WINTER SITE SHUTDOWN

MULTI-WELL EXPERIMENT — REVISED SPRING 1984 SCHEDULE

		MWX-1	MWX-2	MWX-3	MWX SITE
MAR	11	5 HUT-IN	SHUT-IN	SHUT-IN	
	18				REACTIVATE SITE
	25		SQUEEZE JOB AND EVALUATION (REPEAT?)		WGSS TRAILER TO SITE
					SANDIA BSS TRAILER TO SITE
APR	8	PRE-FRAC SINGLE WELL TESTS		VSP SURVEY	
	15		BSS FRAC PREPARATIONS		
	22				
	29	FRAC WELL	MONITOR-BSS-1	MONITOR BSS-2.	FRAC WEEK
MAY	6				
	13	FLOW BACK	RECONFIGURE FOR PRESSURE TESTS		DIAGNOSTICS ANALYSIS
	20	THREE WELL INTERFERENCE TEST			
	27				
JUN	3	PRODUCE	MONITOR	MONITOR	
	10	DELIVERABILITY TESTS			
	17	CROSS-BOREHOLE SEISMIC SURVEYS (LANL)		STRESS TESTS ABOVE PALUDAL	
	24				
JUL	1		STRESS TESTS UP TO COASTAL		
	8				
	15				

DAL 3/20/84

COASTAL STIMULATION EXPERIMENT

	MWX-1	MWX-2	MWX-3
JULY 15	RECONFIGURE	STRESS TESTS op TO COASTAL AND urrt» RED SANDS	RECONFIGURE
22	THREE WELL INTERFERENCE TESTS RED SANDS		
AUGUST 12	PRODUCE	MONITOR	mo-:.TOR
26	RECONFIGURE	STRESS TESTS BETWEEN SANDS AND INTO YELLOW SANDS	RECONFIGURE
SEPTEMBER 9	THREE WELL INTERFERENCE TESTS YELLOW SANDS		
23			
OCTOBER 30	PRODUCE	MONITOR	MONITOR
7			
21		STRESS TESTS ABOVE YELLOW SANDS	
28		SQUEEZE UPPER PERFS	
NOVEMBER 4	PREFRAC PREPARATIONS INCLUDING BSS, SEP AND TILT DIAGNOSTICS		
11			
is		THANKSGIVING	
	FRAC. WELL	MONITOR: BSS-1	MONITOR: ZSS-2
DECEMBER q	FLOW BACK	SITE SHUT-IN ACTIVITIES	
"			
23			

FRAC WEEK

DAN 3/28/8

MWX COSTS AND FUNDING

FY	SANDIA	CER	TOTAL COSTED	CUMULATIVE	FUNDING	CUMULATIVE
80	292	925	1.,217	-	8.,700	-
81	994	713	11707	21924	21241	10.,941
82	1,456	714.01	8.,857	111781	31828	14 1769
83	11507	41222	51729	171510	81769	23.,538
84 (EST)·	11917	31132	5,o IJ9	22,559	2J457	25 1995
85 (EST)	1J900	2J900	4J800	27 J359	31800	29 1795

* INCLUDES $450,000 FOR WGSS SUPPORT

MWX PERSONNEL

	ACTIVITY	PRINCIPAL INVESTIGATOR	FTE (FY84) STAFF	FTE (FY84) ASST.
SANDIA	MANAGEMENT	NORTHROP. SATTLER	1.0	
	CORE ANALYSIS, CORRELATIONS	SATTLER	0.8	1.0
	GEOLOGY. NATURAL FRACTURES	LORENZ	1.5	1.0
	STU'jULATION. STRESS	WARPINSKI	1.0	
	FRACTURE DIAGNOSTICS	ENGI	1.0	2.0
	GEOPHYSICS	SEARLS	0.5	-
			5.8	LI.O
CER	MANAGEMENT	MANN	1.0	
	SITE OPERATIONS	COATS. MATHIS	1.5	
	TEST TRAILER	WILMER	1.0	5.0
	RESER. TEST AND ANALYSIS	BRANAGAN	1.0	1.8
	LOGGING, CORRELATIONS	KUKAL	1.0	1.2
			5.5	8.0
	WGSS SUPPORT	VARIOUS	.L3	2.9
			·6.8	10.9

TECHNICAL REVIEW PANEL

- SELECTED ON BASIS OF EXPERIENCE" ONGOING WORK, AND CONTINUED INTEREST IN TIGHT GAS SANDS

- THERE HAVE BEEN 12 FORMAL MEETINGS (JULY 1979 - FEB.1984) PLUS TOPICAL MEETINGS AND CORE DISPLAYS

- TECHNICAL INTERACTION

- MEMBERS:

L. ELKINS	-	SOHIO
J. FITCH	-	MOBIL
G. MARTIN	-	ARCO
W. McMAHAN	-	SUPERIOR
R. SAUCIER	-	SHELL
C. SHAUGHNESSY	-	EXXON
R. VEATCH	-	AMOCO

MWX STATUS

- FIELD LABORATORY ESTABLISHED
- STIMULATION EXPERIMENTS UNDER WAY
- CLOSE, EFFICIENT MWX TEAM
- RECOGNIZED PROGRAM
- BASE FUNDING LEVEL

MWX NEEDS

- SCHEDULE VS TESTING
- LENS MORPHOLOGY; SEISMIC DEVELOPMENT
- FRACTURE GEOMETRY; DIAGNOSTICS DEVELOPMENT
- OPTIMAL, MULTI-YEAR FUNDING
- STEP-OUT OPPORTUNITY

MULTI-WELL EXPERIMENT - AN OPERATIONAL OVERVIEW

CER Corporation

Las Vegas, Nevada

Robert L. Mann

November 1979 to Present

Present Contract - 37-1075

Site Operations and Testing

CER.

MULTI-WELL EXPERIMENT

A RESEARCH ORIENTED FIELD LASORATORY

OBJECTIVES

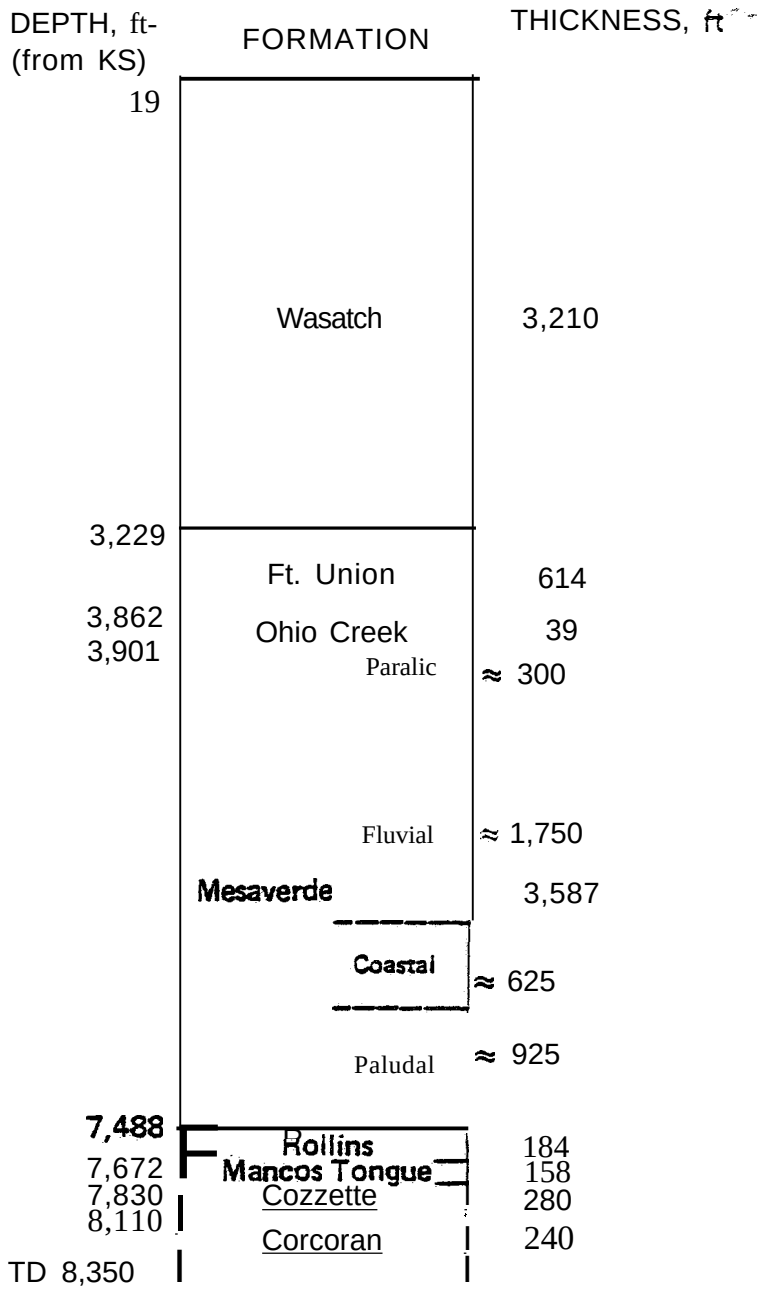
- Determine size, shape, orientation and distribution of lenticular sands.
- Determine in situ reservoir properties and quantify their variations.
- Improve **reliability** and accuracy of log interpretation in tight gas sands.
- Determine effects of earth stresses upon stimulation and gas production.
- Conduct stimulation experiments to evaluate technology and answer key questions.

CER.

SITE SELECTION CRITERIA

- Be in an area of proven Mesaverde production
- Be in an area that is typical of lenticular sand production in the region
- Be a reasonably accessable location
- Be suitable for year around operations
- The objective horizons be at reasonable depths
- The operator or lease owner agreeable to a long term experiment

CER



GEOLOGIC CROSS SECTION
OF MWX-1

CER

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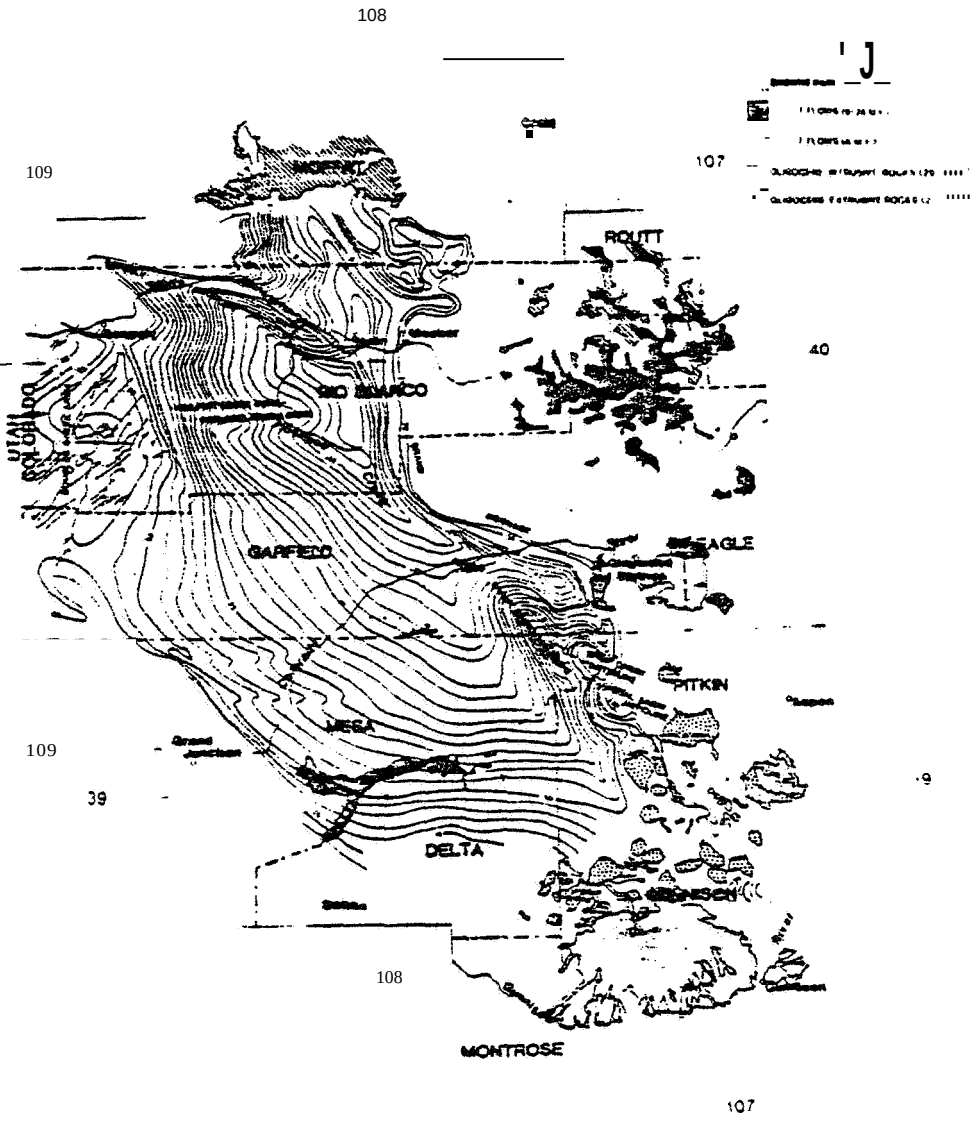
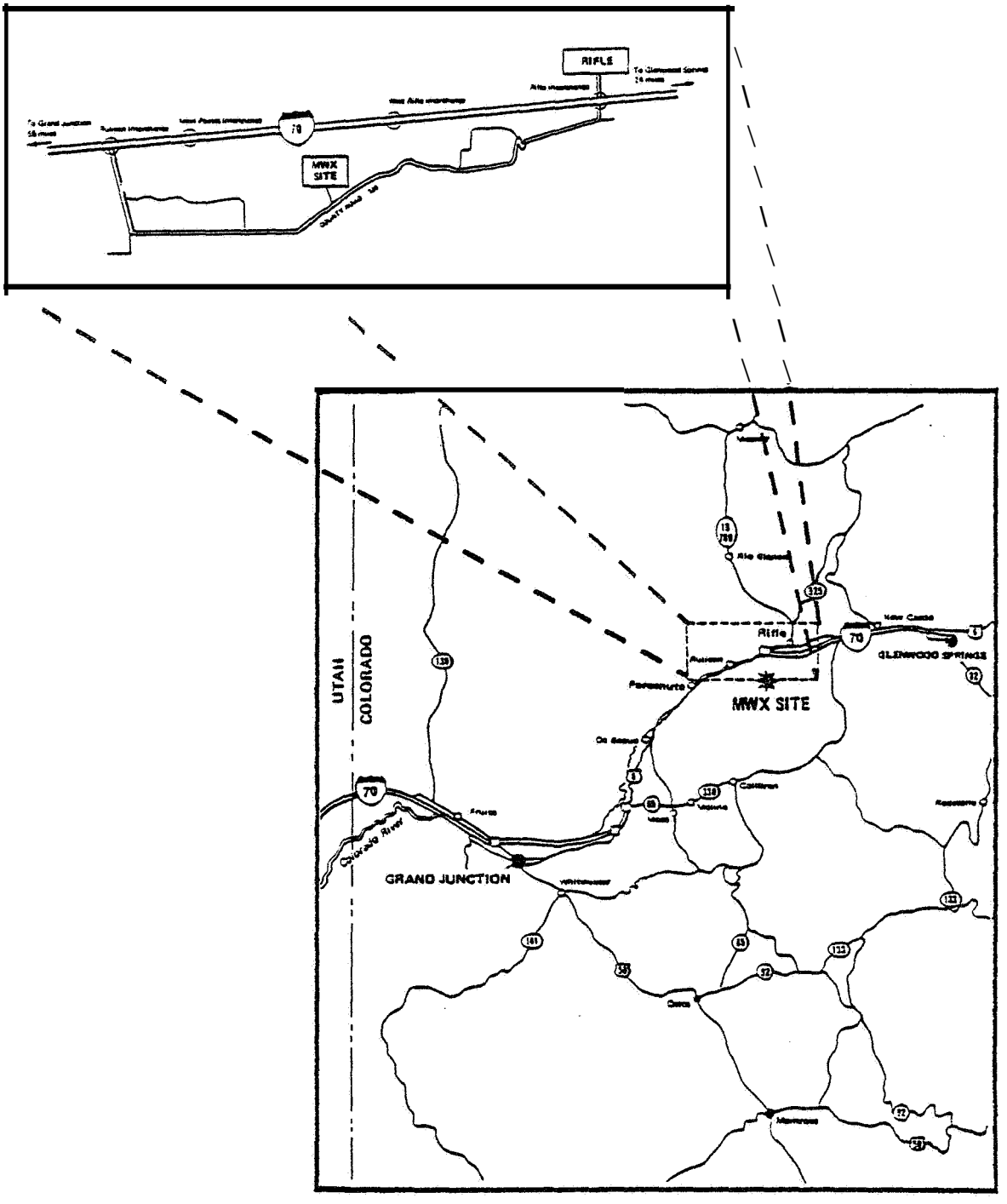
Contour of the Rollings-Trout Creek Structure

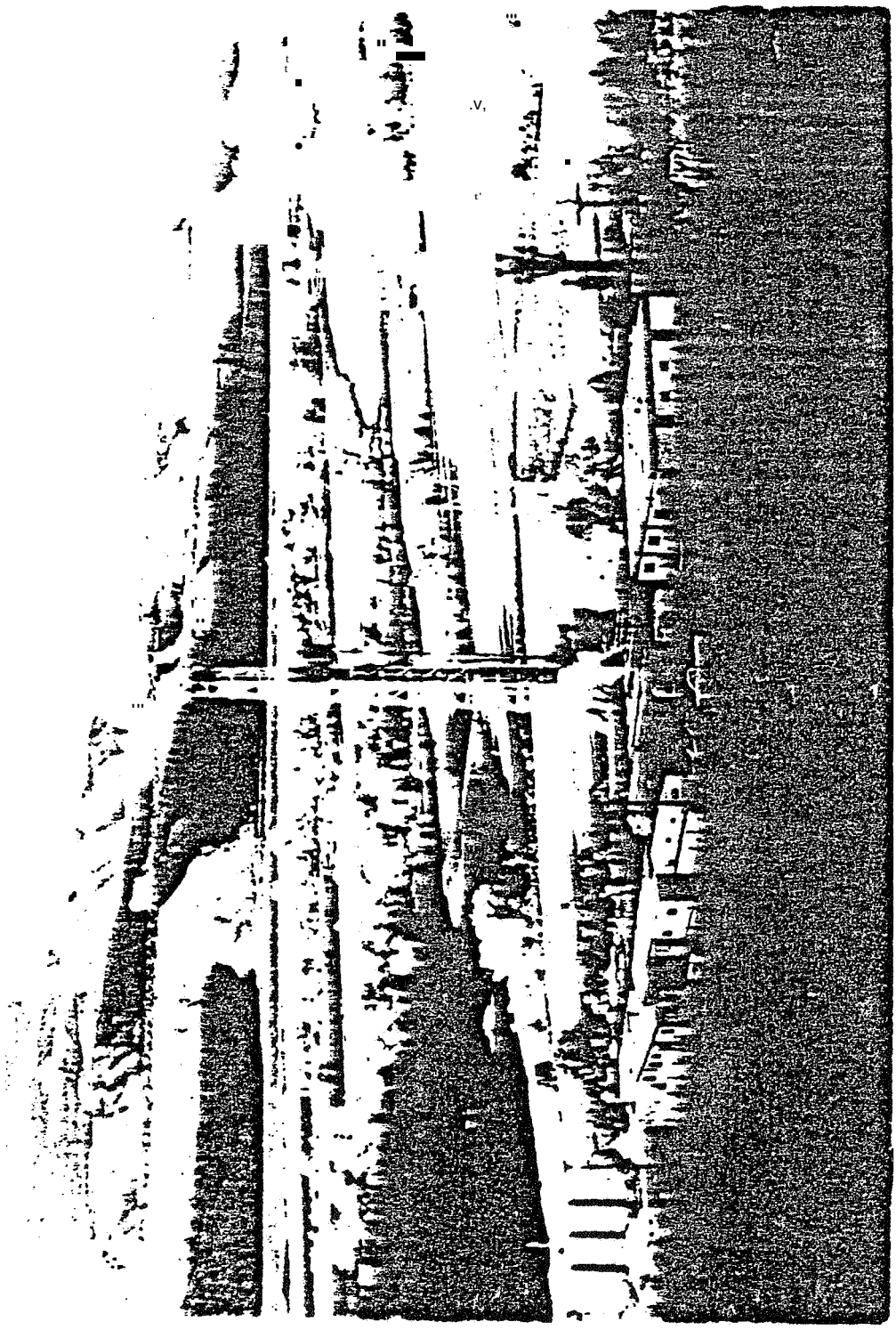
By Ronald C. Johnson. U·S·G·S·

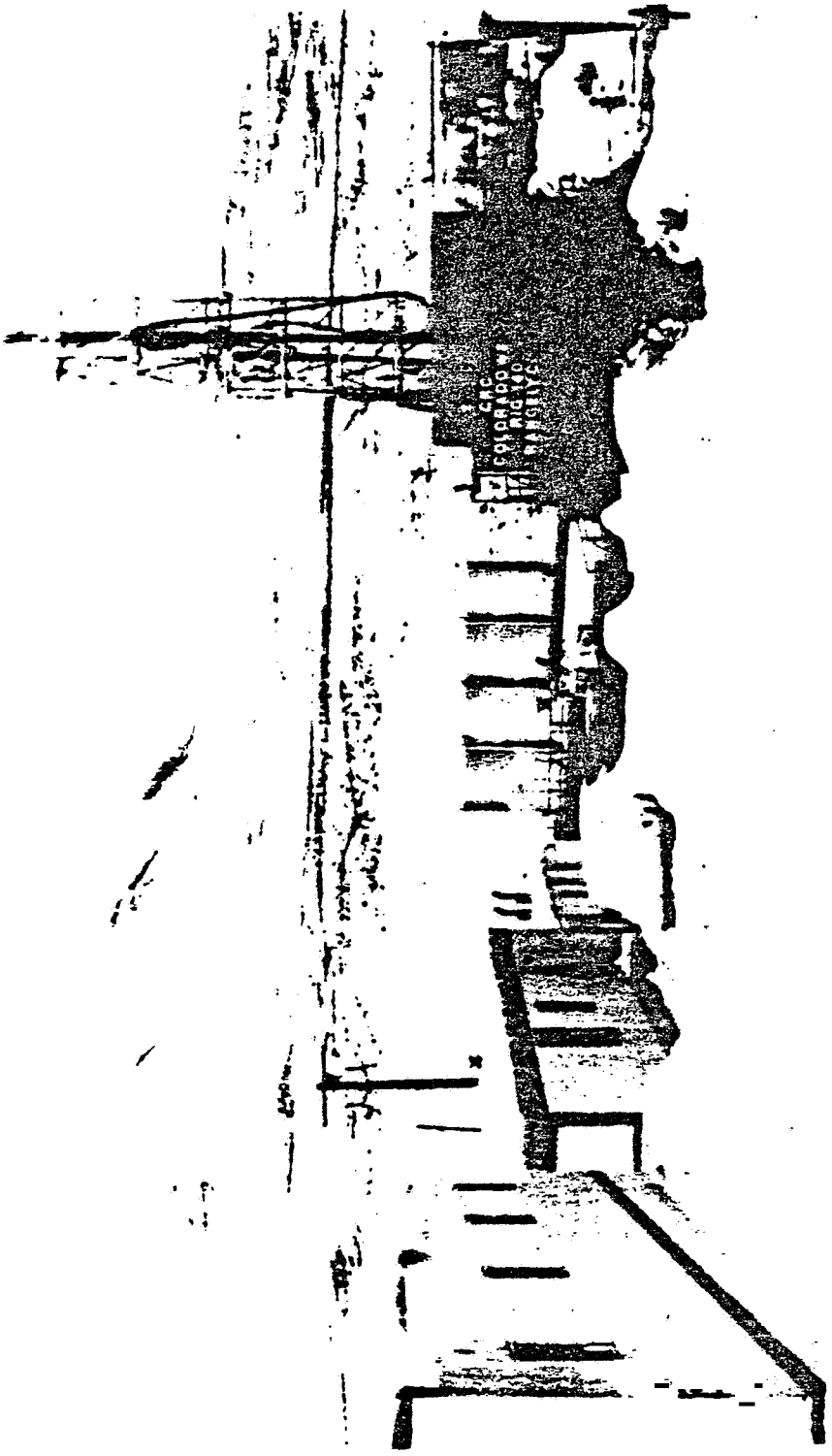




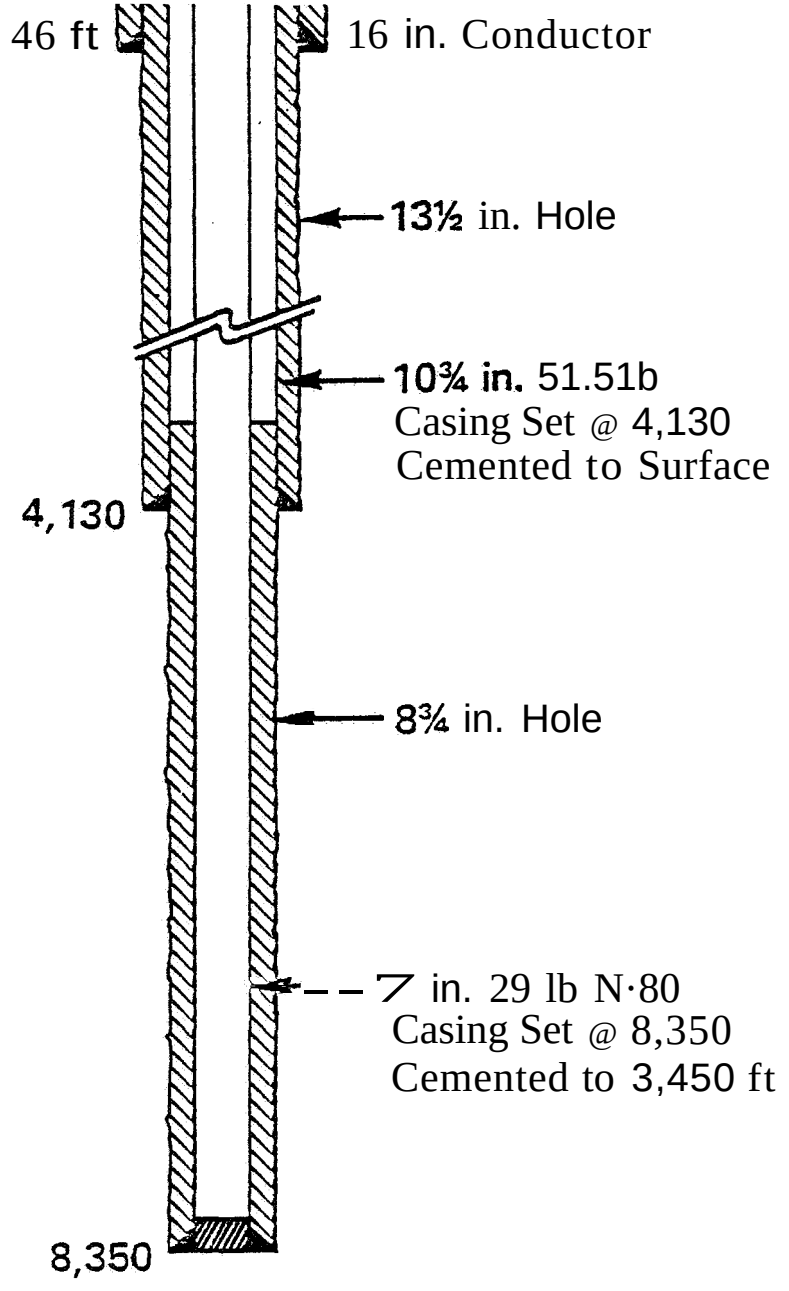
MAP OF WESTERN COLORADO SHOWING MWX **SITE**

CeR.





MWX-1



CORES

4,170 · 6,827 ft	2,657 ft
7,870·7,960	90 ft
Total	2,747 ft
Oriented	470 ft

LOGS

4,130 . Surface
4 Logs . comb.

6,827 . 4,130 ft
11 logs· comb.

8,350 . 4,130 ft
18 logs .. comb.

DSTs

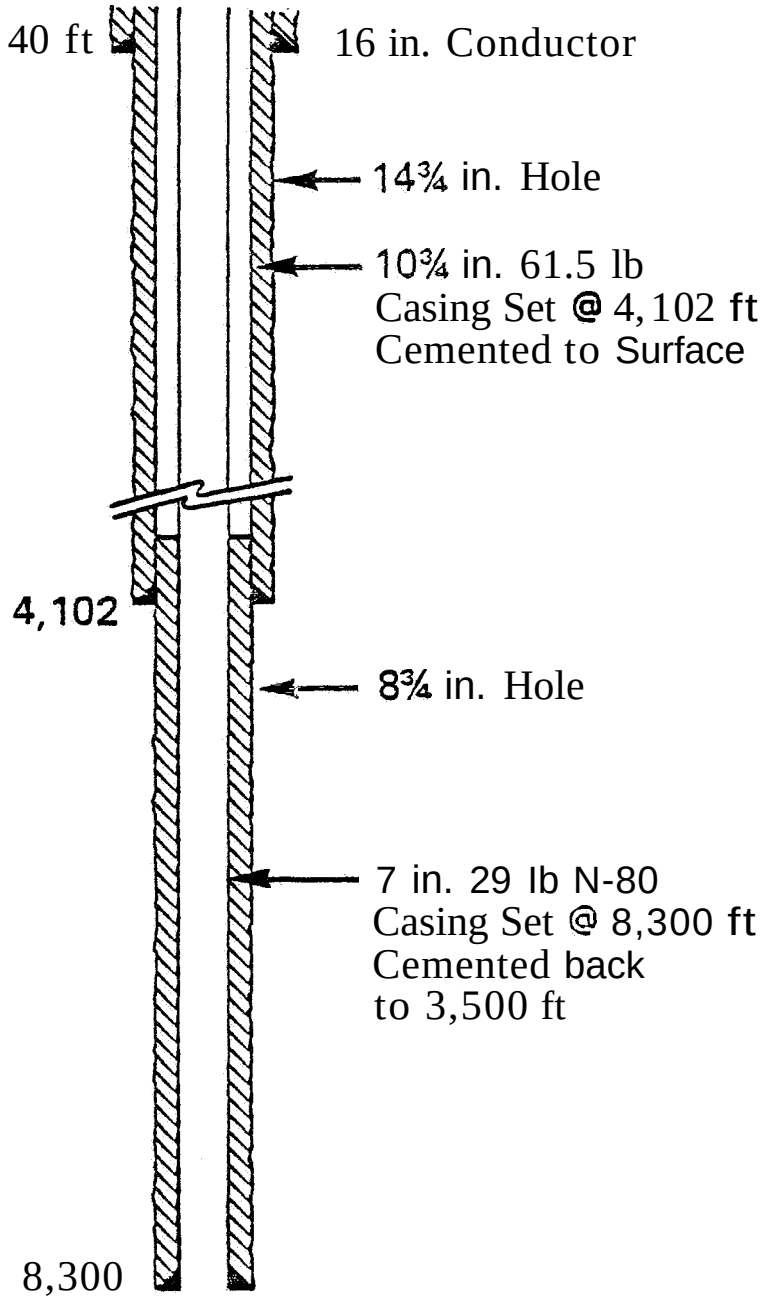
5,885 . 5,830 ft

RFTs

8,135 -4,535 ft
12 tests

Spud Date: Sept. 13, 1981
Rig Released: Dec. 21, 1981

MWX-2



CORES

4,870 - 4,956 ft
5,485 - 5,581 Pressure Core
5,700 - *5,880*
6,390 - 6,568
7,030 - 7,385
7, 817 - *7,907*
8,100 - 8,141

915 ft of Core
395 ft Oriented

LOGS

5,438 - 4,094 ft
3 logs - comb.

6,050 - 4,094 ft
3 logs

6,688 - 4,094 ft
9 logs - comb.

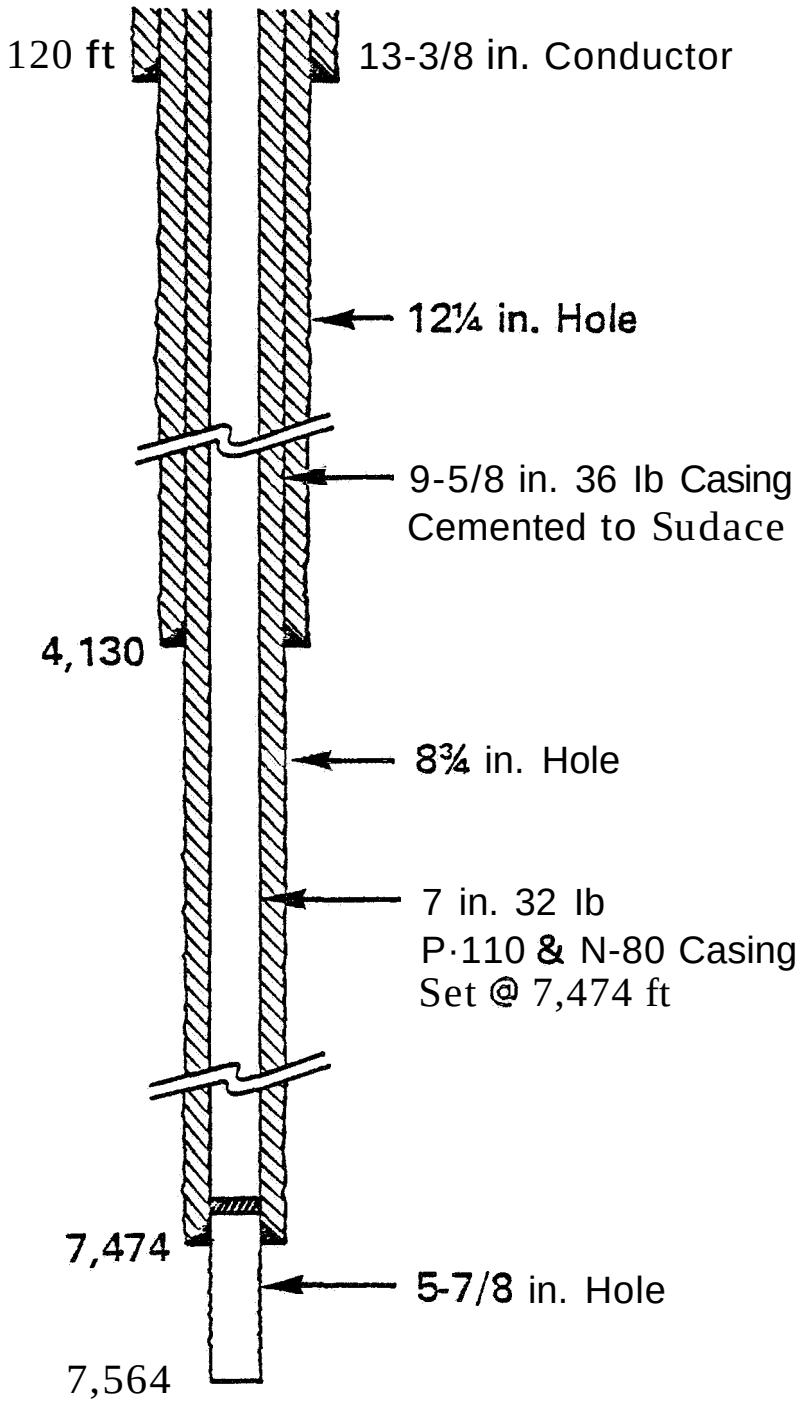
8,300 - 4,094 ft
15 logs - comb.

DST

4,895 - 4,955 ft

Spud Date: Dec. 31, 1981
Rig Released: Mar. 30, 1982 91 days

MWX-3



CORES

4,887 . 4,928 ft
5,690· 5,870
6,431-- 6,528
6,875· 6,910
7,071 - 7,160
7,536 - 7,564

435 ft of Core
All Oriented

LOGS

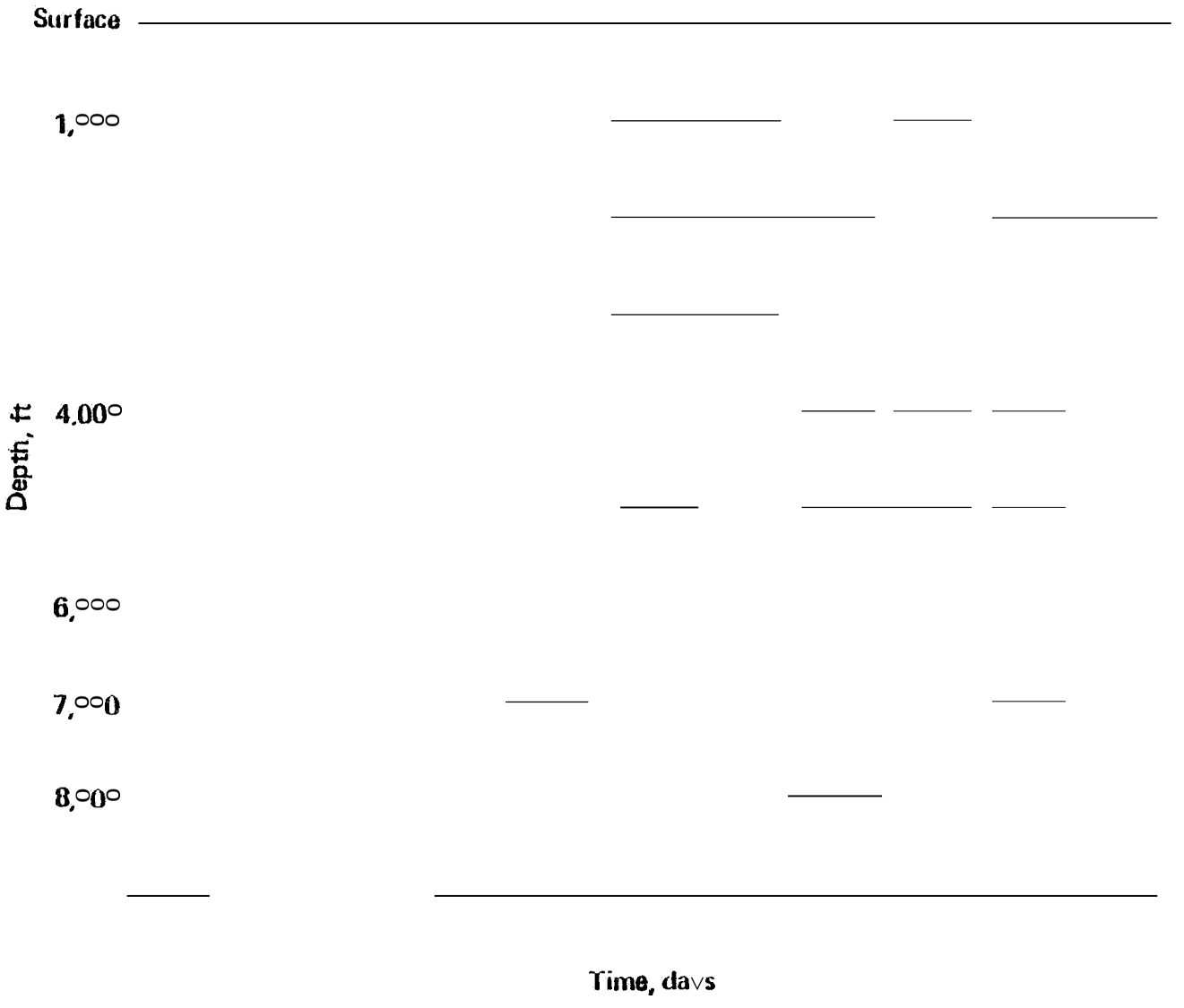
4,134· Surface
4 logs. comb.

5,875 ·4,129 ft
5 logs· comb.

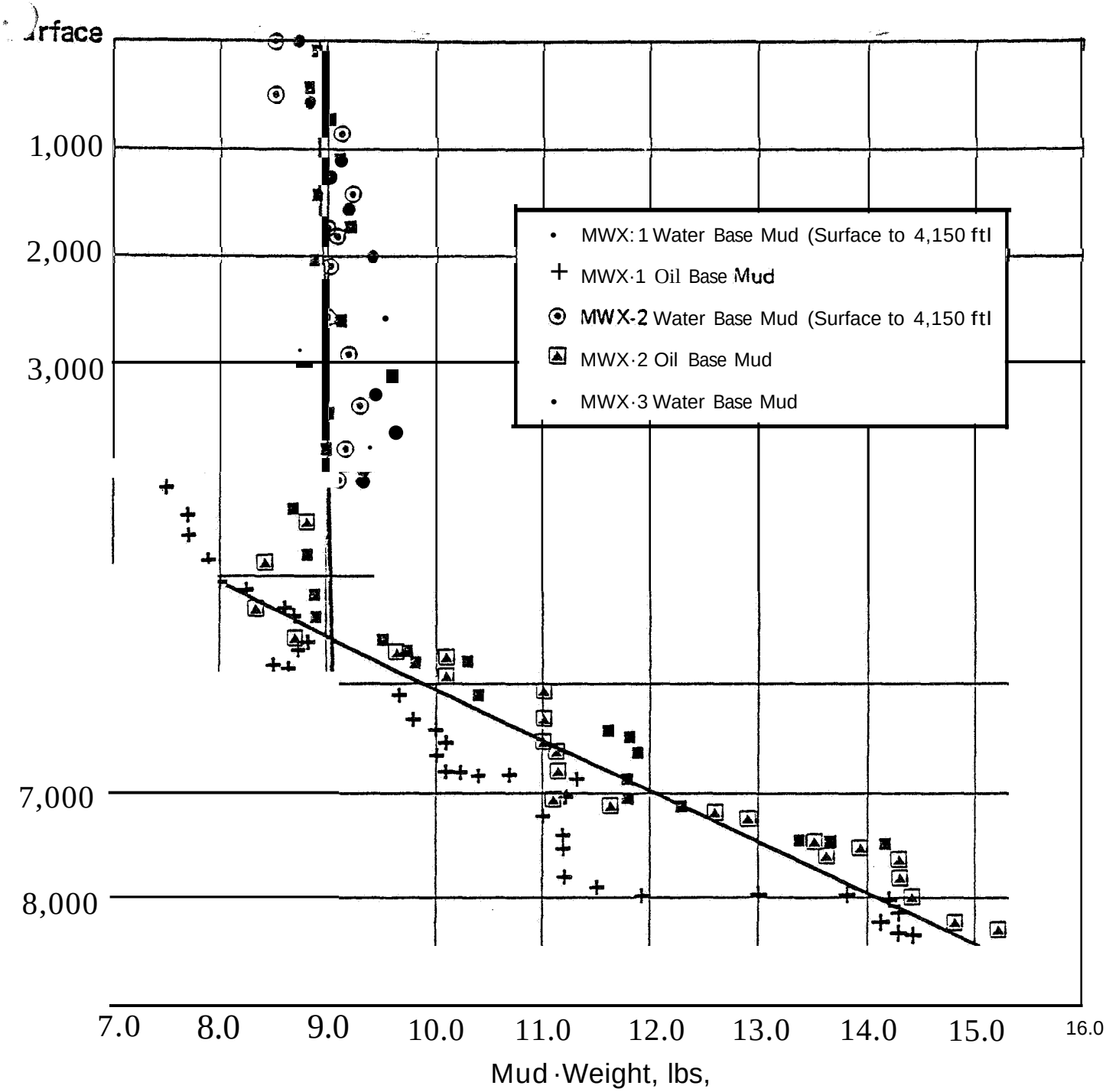
6,.875 . 4,130 ft
7 loqs- comb.

7,463 . 4,129 ft
28 logs· comb.

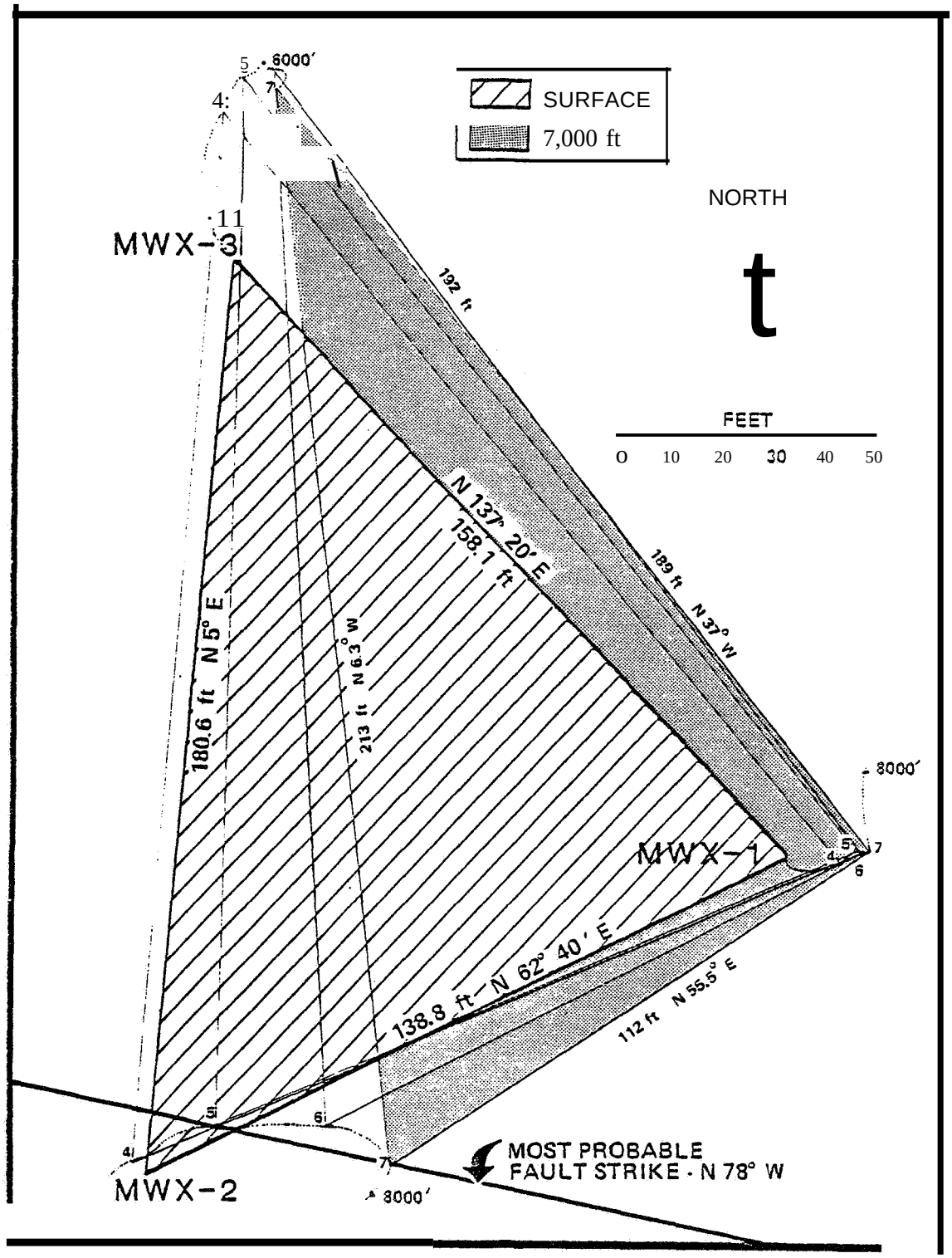
Spud Date: June 7, 1983
Rig Released: Aug. 17, 1983 72 days



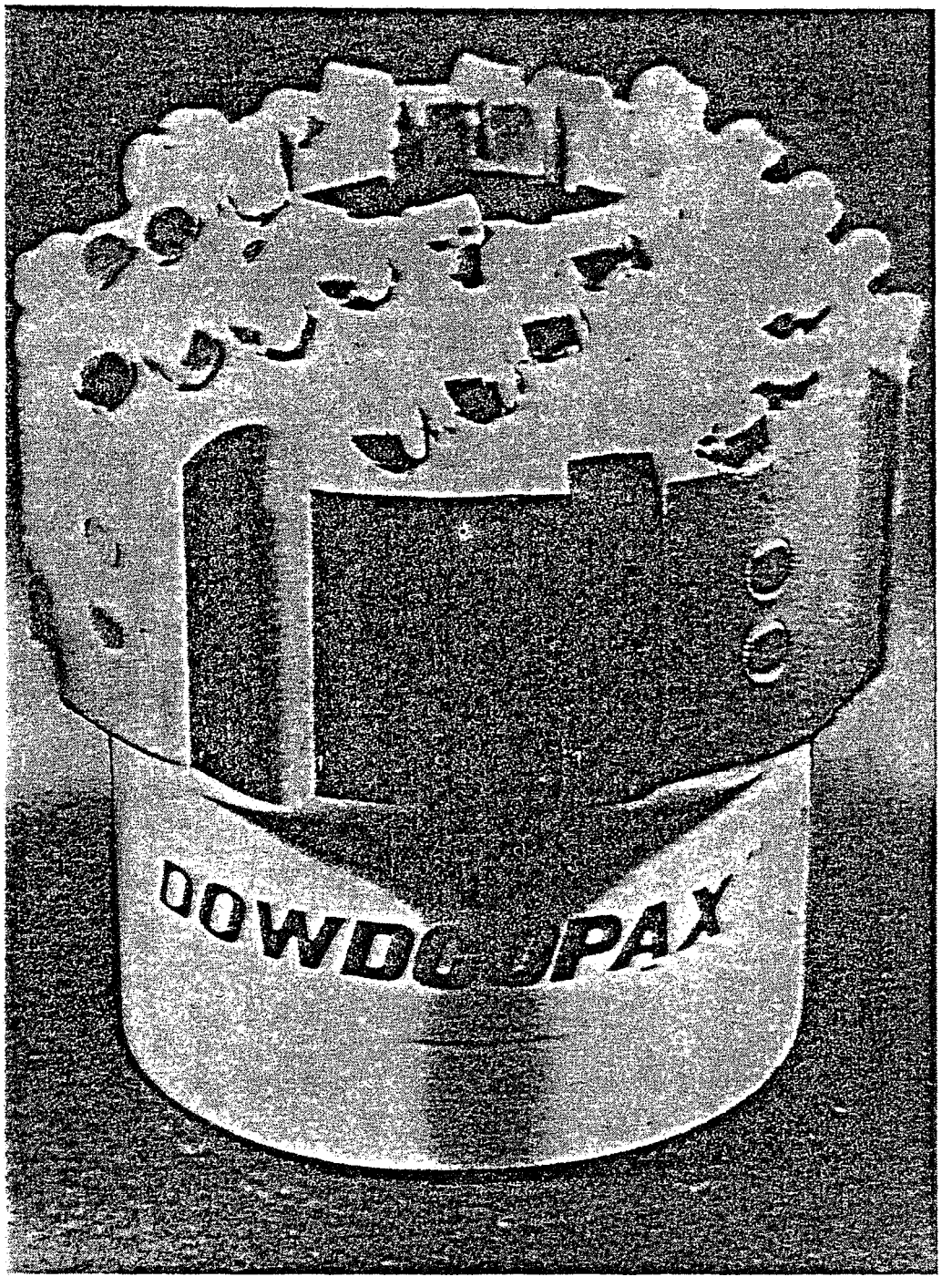
DRILLING TIME VS. DEPTH



MUD WEIGHT VS. DEPTH



MWX SPACING AT SURFACE AND AT 7,000 ft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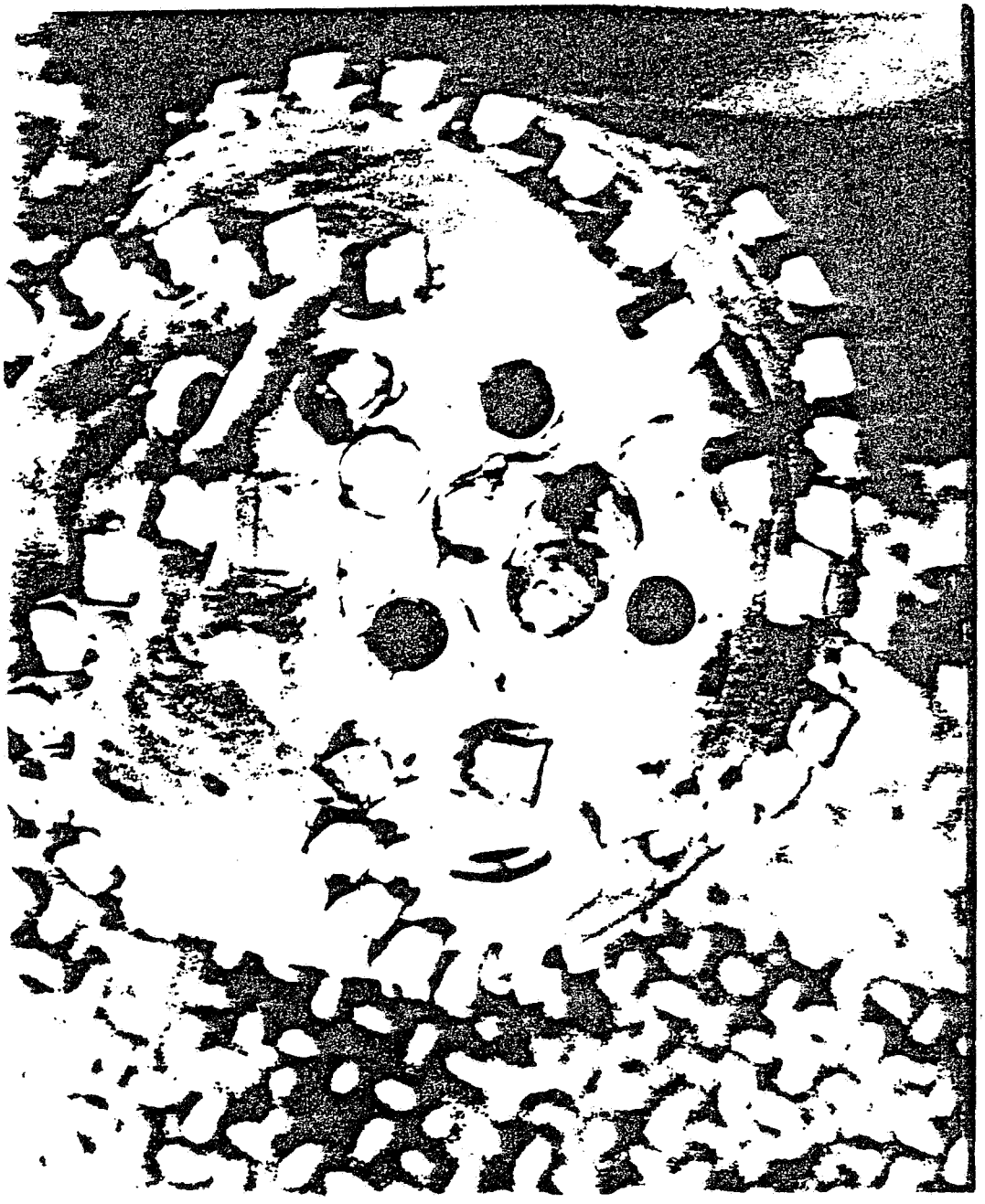
Core Program Summary

Core No.	Depth, ft	Amount Recovered ft	Bit Type	Coring Time, hrs	Average Rate, ftlhr
1	4,170-4.221	51	Diamond	24.33	209
2	4,221-4,281	60	Diamond	22.50	2.66
3	4,281-4.341	60	Diamond	13.55	4.42
4	4,341-4,348	7	Diamond	1.50	4.67
5	4,348-4.408	60	Diamond	21.33	281
6	4,405-4,465	60	Stratapax	3.00	20.00
7	4,465-4,565	60	Stratapax	3.00	20.00
8	4.525-4,585	60	Stratapax	4.42	13.57
9	4.585-4,645	60	Stratapax	3.17	18.92
+10	4.645-4.705	60	Stratapax	4.00	15.00
+11	4,702-4,762	60	Stratapax	7.67	7.92
+12	4,762-4,822	60	Stratapax	8.65	6.93
13	4,822-4,882	60	Stratapax	7.25	8.27
14	4.882-4,942	60	Stratacex	3.25	18.46
15	4,942-5,002	60	Stratapax	7.50	8.00
16	5.002·5,062	60	Stratapax	5.92	10.13
17	5,062-5,120	58	Stratapax	7.87	7.24
18	5,120·5.180	60	Diamond	12.25	4.89
19	5,180-5,204	24	Diamond	10.75	2.23
20	5,204-5,264	60	Stratapax	3.50	17.14
21	5,264-5,324	60	Stratapax	8.42	7.12
22	5,324-5,384	60	Stratapax	6.50	9.23
23	5,384-5,444	60	Stratapax	8.38	7.15
*24	5,425-5,485	60	Stratapax	10.00	6.00
*25	5,484-5,534	50	Stratapax	8.00	6.25
26	5,534-5,592	58	Stratapax	10.00	5.80
27	5.592-5.652	60	Diamond	14.33	4.18
28	5.652·5.712	60	Diamond	16.85	3.56
29	5.712-5,772	60	Stratapax	4.66	12.87
30	5,772-5.825	53	Stratapax	14.00	3.78
31	5,825-5,885	60	Stratapax	5.15	11.65
32	5.885·5.932	47	Stratapax	6.37	7.37
33	5.932·5,992	60	Stratapax	6.42	9.34
34	5,992-6,054	62	Stratapax	10.42	5.95
35	6.054-6.114	60	Stratapax	4.88	12.29
36	6.114-6.119	5	Stratapax	4.60	1.08
37	6,119-6,168	49	Stratapax	8.13	6.02
38	6,168-6,258	90	Stratapax	10.25	8.78
39	6,258-6,348	90	$tratapax	14.50	6.20
40	6,348-6,438	90	Stratapax	22.38	4.02
+41	6,438-6,528	90	Stratapax	14.00	6.42
42	6.528·6,618	90	Stratapax	21.57	4.17
43	6,618-6,689	71	Stratapax	15.75	4.50
44	6,689-6,779	90	Diamond	23.12	3.89
45	6.779-6,827	48	Diamond	14.62	3.28
+46	7,870-7.960	90	Diamond	33.62	2.67

+denotes oriented core



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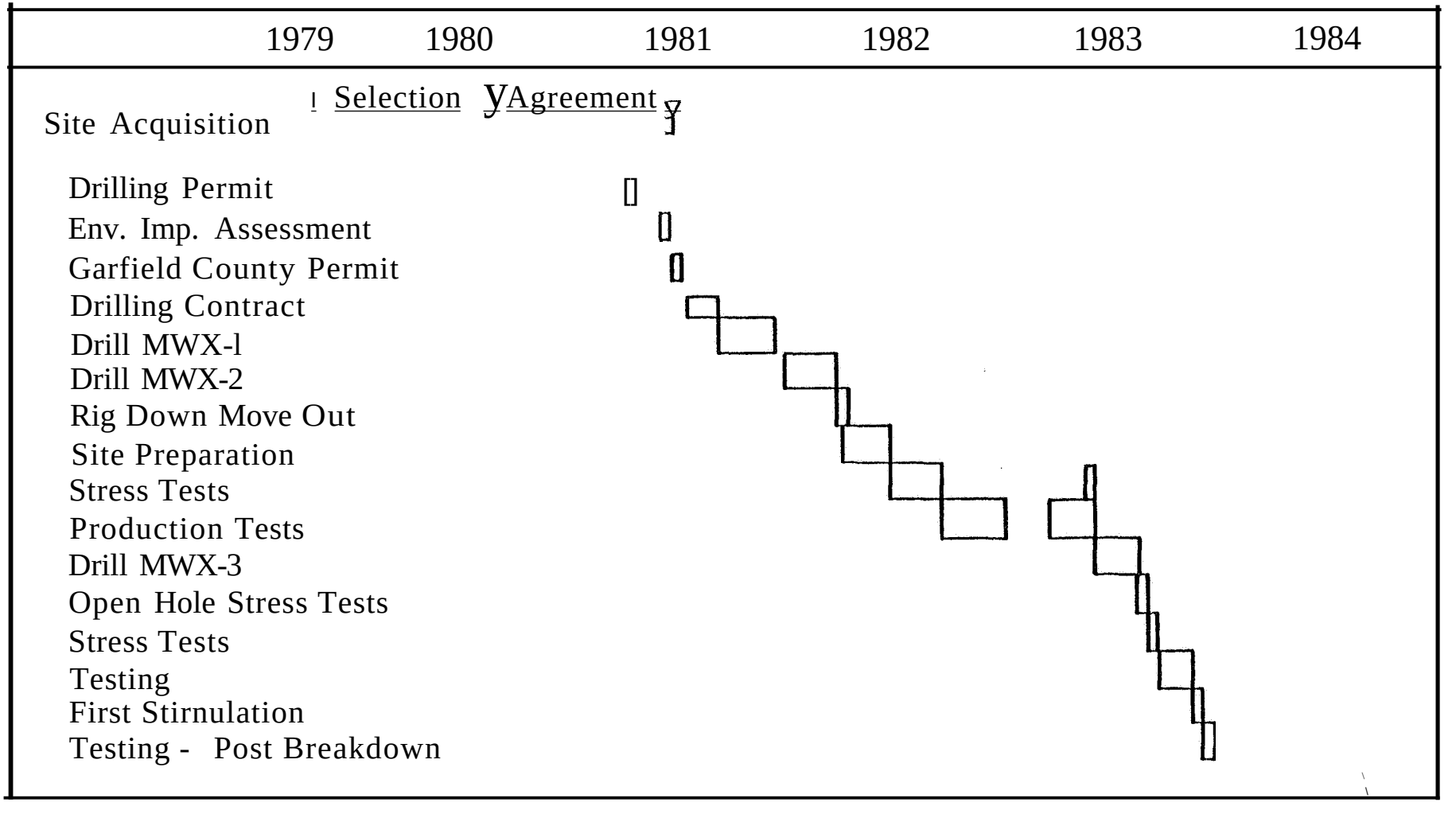
".INo	Size & Make	Tvp.	Jets 32.... 1	2	3	Depth Out, ft	Footage	Hours	Accumulati.. hours	Penetration ....../hr	Weight, 1,000 lbs	Rotary Speed, rpm
	,.I", in Hughes Tool	OSC3AJ	III	1"	1"	'91	'51	38S	385	390	5/15	40/125
	13½... Hughes Tool	OSC3AJ	15	15	'5	..96	299	190	515	15.10	10/15	75/120
1	13½ ,.) Hughes Tool	OSC3AJ	14	14	'4	638	142	IOS	880	4.10	10/20	20/70
·1	13½ in Hughe Tool	OSC3AJ	1"	14	14	1,421	783	.30.0	t180	26 10	25/35	65/75
"	IJ", In 'hughes 100'	OSCIAJ	'4	14	14	1,866	245	13.0	131 0	1890	15/20	75/100
"	'J"'.,n Hughes Tool	OSC3AJ	14	14	14	2,174	508	510	182.0	10.00	20/30	50/75
1	,3"/,... thughe, Tool	OSC3AJ	16	16	16	2,791	617	51.0	233.0	12.00	20/30	11I01125
:1	13½ in Hughes Tool	OSC3AJ	16	16	16	3,100	300	25.5	258.5	12.10	20/30	100/120
'I	13½ .) Hughes Tool	OSCJAJ	16	'6	16	3,233	133	'4.0	272.5	940	20/55	80/120
10	13½ in Hughes Tool	OSC3AJ	'6	'6	16	3,261	28	4.5	277.0	6.20	18/30	80/100
5111	13½ .. Hughes Tool	OSC3AJ	16	'0	16	3,339	18	24.5	IOU	3.20	25	100
11	13½ in Hughe Tool	OSC3AJ	16	16	16	3,546	207	28 0	379.5	7.40	25/35	100
'11111	13½ ,it'Hughes Tool	OSC1AJ	16	16	16	3,642	96	no	342.5	7.40	25/35	100
11111	13½ in Hughes "'01	OSC3AJ	16	'6	UI	3,658	'6	3.5	346.0	4.60	25/30	100
12	13½ in Hug..... Ionl	OSC1JJ	16	16	]'	3,74	81	12.5	358.5	6.60	25/30	100
I I	12Y. in II...phes 1001	J 4	'0	16	16	3.90'	160	33.5	302.0	4.80	25/30	10
14	12½ in Hughes Tool	J 33	16	18	18	4,130	229	20.0	412.0	11.50	20/45	50/70
1110	13½ in Hughes Tool	f 2	16	16	18	4,130	Rear"	23.0	435 0	–	10115	50/70
I',	9½ in Hughes Tool	J1	10	18	18	...no	40	'0.0	445.0	4 00	20/25	75
1CB	8½ 'n. Amer Coldset	Ell STAR	1FAO.JO			4,341	11'	58.0	503.0	3.00	22/25	GO
2CB	o½ '0 Amer Coldset	RM ft.AS"	1FA 0.32			4,405	64	22.0	525.0	'.90	25/28	60/80
11:11	8½ in. u owdco	5" stapax	TfA 1.035			4,685	100	11.5	530.5	15 JO	5/7	50
4CB	8½ in Dowdco	Stratapax	TFA 1.005			5,002	417	43.5	580.0	9.60	1/10	60
3CIIIII	8½ in Dowdco	5'..,..nax	TFA 1.035			5,120	118	13.5	593.5	8.JO	6/10	60
1fi	8½ in I"sf.... 1oo1	J·11	'6	'8	18	5,120	Ream	1.5	595.0	–	6110	60
5CB	O½ in. Unwdco	MV 20	TFA 0.46			5,204	04	21.5	616.5	3.90	20/25	60
6CB	8½ in Dowdco	Stratap..	TFA 1.035			5,444	240	26.0	642.5	9.20	8110	60
1fiIIII	8½ in Hughes 'oo1	J·33	16	18	]'	5,444	Ream	1.5	644.0	–	5/6	GO
/ell	8½ in Dowrteo	Stratapax	TFA 1.035			5,592	148	29.5	673.5	5.00	OIIO	60
5CIIIII	8½ in Dowdco	MV 20	TFA 0 48			5,712	120	31.5	705.0	380	15/25	60
6CIIIII	8½ in Dowdco	51ratapax	TFA 1.035			5,825	113	18.5	723.5	8.'0	8/10	60
8CB	8½ in Dowdco	5tra'apax	1FA 1.035			6,054	229	33.0	756.5	6.90	BIIO	60
11:1\1111	8½ In Dowdco	St,ratapax	TFA 1.035			6,258	204	25.0	JBI.5	8.20	8/12	55
4CIIII	8½ in Dowdco	Stra.apax	TFA 1.035			··438	180	32.5	814.0	5.50	8/12	55
6CIIIII	8½ in Dowdco	5".'apax	IfA 1.035			6,618	180	35 5	849.5	5 '0	8/12	55
":111111	8½ In Dowdco	Sir.,apax	IfA '.035			6,689	71	17.5	867 0	".10	8/14	55
'IUII /	8½ 'A Dowdco	MV 20	TFA 0 46			8,827	138	39 5	906 5	3.50	75	80
11	8½ ,n Hughes Tool	JO4	'4	14	14	6,859	32	10 0	916.5	J.20	24/26	100
III	8½ in Dowdco	Stratapax	16	'6	,tI	7,863	1,004	126 5	1,043 0	190	12/14	SO
'InIIU'	8½ 'n Dowdco	MV 20	TfA 0 46			7,955	92	JOO.	1,073 0	JOO	20/25	10
"ifiII	8½ in Dowdco	Stratapax	'6	'tl	'6	8,009	54	28 5	1,099 5	2 00	14/16	50
'''	8½ in Hughes Tool	J .:1	III	'8	'8	8,350	341	120 5	1,220 0	2 80	40/48	50

OPERATIONALPROBLEMS

1. High Pressure Wells - (Overpressured)
2. Severe Downhole Environment ~210°
3. Keeping 3 Downhole Instruments Operational
4. Leaky Packers
5. Long Lubricators
6. Surface Leaks
7. Freezing Problems in Lubricator
8. Sufficient Crews for Twentyfour Hour Operations
9. Severe Weather
10. Royalty Payments for Gas Flared During Testing

----------CER



SCHEDULE OF EVENTS MULTI--WELLEXPERIMENT

USGS Research in Support of MWX

by

C. W. Spencer, J. K. Pitman, V. F. Nuccio, and R. C. Johnson

MAJOR GOAL OF RESEARCH

The major goals of the U.S. Geological Survey MWX (Multi-Well Experiment) work are to provide geologic characterization and related research in support of the ongoing petroleum engineering, petrophysical, log analysis, and well stimulation work. at the U.S. Department of Energy's (DOE) MWX field laboratory. A critical additional goal is to characterize the geologic conditions at the MWX site. This characterization will then be correlated to other parts of the Piceance basin and, more importantly, to analog basins so that the research results at MWX will have broad application to the identification of, and the enhanced recovery of gas from tight reservoirs elsewhere in the United States.

Specific objectives of this work. are to characterize the geologic setting of the MWX site in terms of its 1) regional structure (figure 1), 2) general stratigraphy, 3) tectonic history, 4) gas generation and migration, 5) mineralogic and petrologic character of the reservoirs, 6) microscopic character of porosity and permeability, and 7) the relationship of these factors to log analysis and well-stimulation recommendations. Other objectives are a regional study of the Piceance basin including the thermal history and related gas generation and migration in the MWX area and the Piceance basin in general. Additional objectives include research directed toward providing data to Sandia National Laboratory (SNL)l that will aid in determining the origin and timing of the formation of the natural fracture systems and the conditions under which they formed. The USGS also is responsible for providing quality assurance to DOE for support geologic work done by other contractors. This report has not been reviewed for conformance to stratigraphic nomenclature standards as used by the USGS.

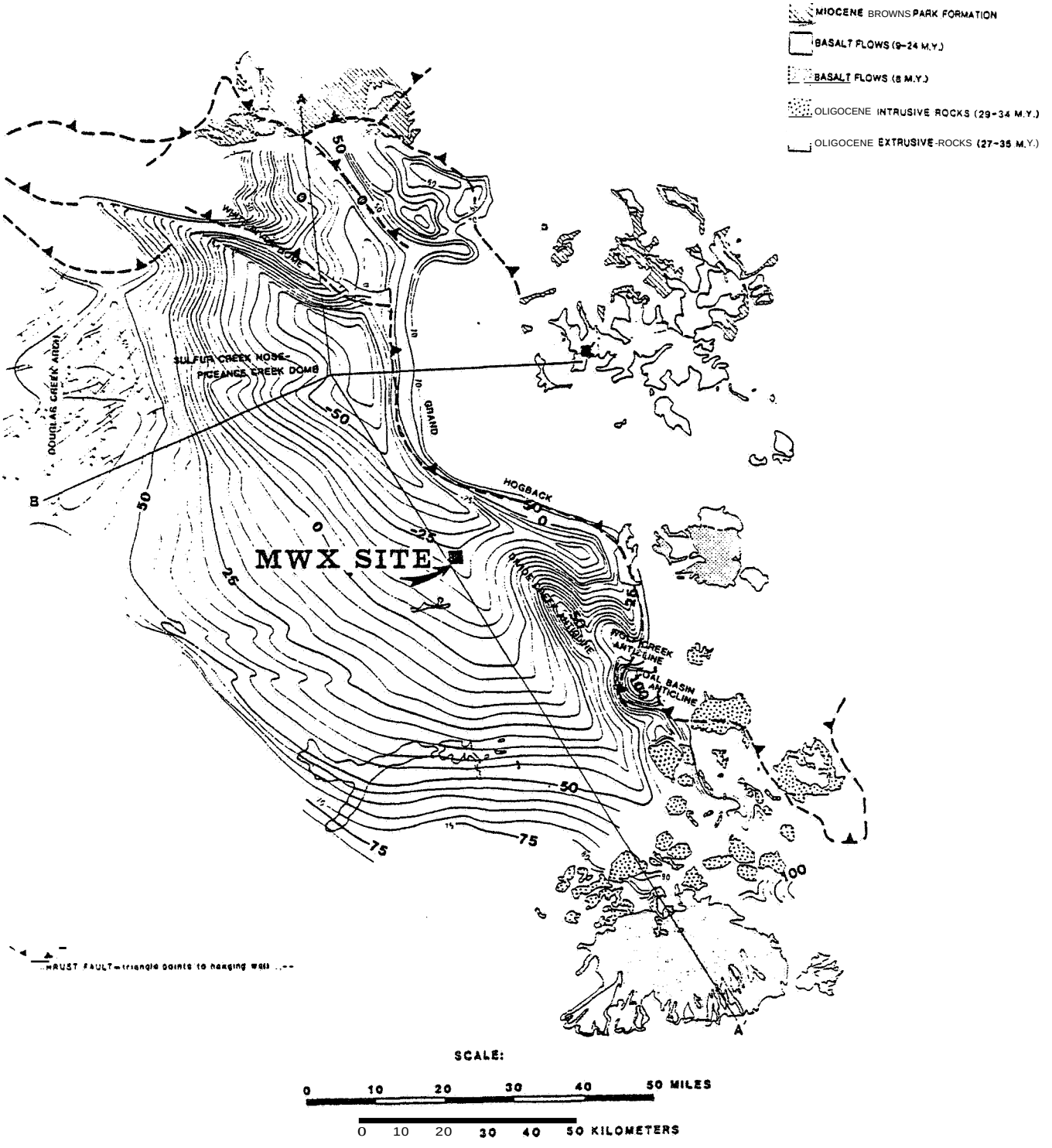


Figure 1.--Structure map of Piceance Basin on top of the Rollins Sandstone in Mesaverde Group by R. C. Johnson (1983). Cross sections A-A' and B-B' are not included in this report.

BUDGET AND COST EFFECTIVENESS

The USGS has had an ongoing research program in the major tight gas areas in the Western United States. A formal Interagency Agreement was initiated in 1978 at the request of DOE. A part of this program involved work in the :Piceance basin. This pre-MWXwork was of considerable value in site selection and provided the USGS and others with background geologic information for some aspects of the design of the MWX research. To date, the USGS has published 32 papers and maps on the MWX-Piceance research in cooperation with the DOE Western Gas Sands Subprogram. In addition, a number of unpublished reports on various aspects of MWX have been prepared. DOE funding for MWX-Piceance basin work by the USGS:

Prior years -	$658K
FY'84	175K

We believe the work has been cost effective in that all persons working directly on this project had previous experience in the geology of the basin (primarily in oil shale or oil and gas research) and, therefore, did not have to go through a learning period relative to the structure, stratigraphy, tectonics, etc. of the area. Further cost effectivenss resulted from USGS persons in other research groups becoming interested in the MWX research needs that complemented their own interests and data needs. This work by other groups has been done at no cost to DOE (e.g. water analysis, some vitrinite reflectance studies, gas isotope studies, previous fracture and lineament studies, etc.).

Perhaps one of the most cost-effective aspects of the research is that the USGS already had all the necessary laboratory and lIbrary facilities, and data bases (P.I. well records, microfilm logs and well histories, etc.); therefore, no further acquisitions of data or equipment have been necessary. In fact DOE, and the U.S. taxpayers, have realized a considerable saving on all DOE energy research involving well data (Devonian Shale, Geopressured Aquifers, etc.) through access to the USGS contract with Petroleum Information (P.L).

CONTRIBUTIONS TO EXISTING RESEARCH

The main contributions of previous USGS research were to assist in MWX planning, log program and core program and analysis and assist DOE and CER in MWX site selection. Six basinwide well-log cross sections that showed well-log character, drillstem test recoveries (including field recorded pressures), perforations tests, reservoir facies and lithology, and cores were published by Johnson, Granica, and Dessenberger (1979). One of these sections (USGS MF-1130B) is close to the MWX site.

Other contributions to existing research include cooperative studies and publications coauthored with: 1) CER (log analysis), 2) SNL (VSPseismic, pore geometry analysis, NMR determination of porosity and permeability), 3) Mobil Research (natural fractures and fracture-filling cements), and 4) IGT (core mineralogy and interpretion of core data). The USGS reviews Bendix Field Laboratory petrographic reports and does additional studies, as needed, on more complex mineralogic problems. One such effort identified a high iron chlodte clay in MWX core that had previously been identified as kaolinite. The presence of iron-bearing chlorite is important to recognize when designing well stimulations because this clay is highly soluble in dilute HCl and can form ferric hydroxide, which has adverse effects on the production potential of a reservoir.

Various zones (facies) of the MWX wells are being studied and interpretations are made relative to the mineralogic and petrographic impact on well-log interpretation and well stimulation. Several sandstones ()15 ft thick) in the 3 wells were correlated and the quality of correlation from well-to-well was rated.

Thermal maturation (gas generation) of source beds are being studied by N. H. Bostick and V. F. Nuccio using vitrinite reflectance analysis. Amoco Prod. Co. also is studying vitrinite reflectance to supplement our investigations. V. F. Nuccio and R. C. Johnson have prepared a thermal maturity map of the Piceance basin so that the MWX well can be related on the basis of thermal maturation (gas generation) to the rest of the basin and to other basins. Figure 2, is a reduced-scale figure of this coal rank (thermal maturity) map. It is keyed to the Rollins Sandstone structural horizon and was compiled from vitrinite reflectance, coal calorific values (BTU) and ASTM

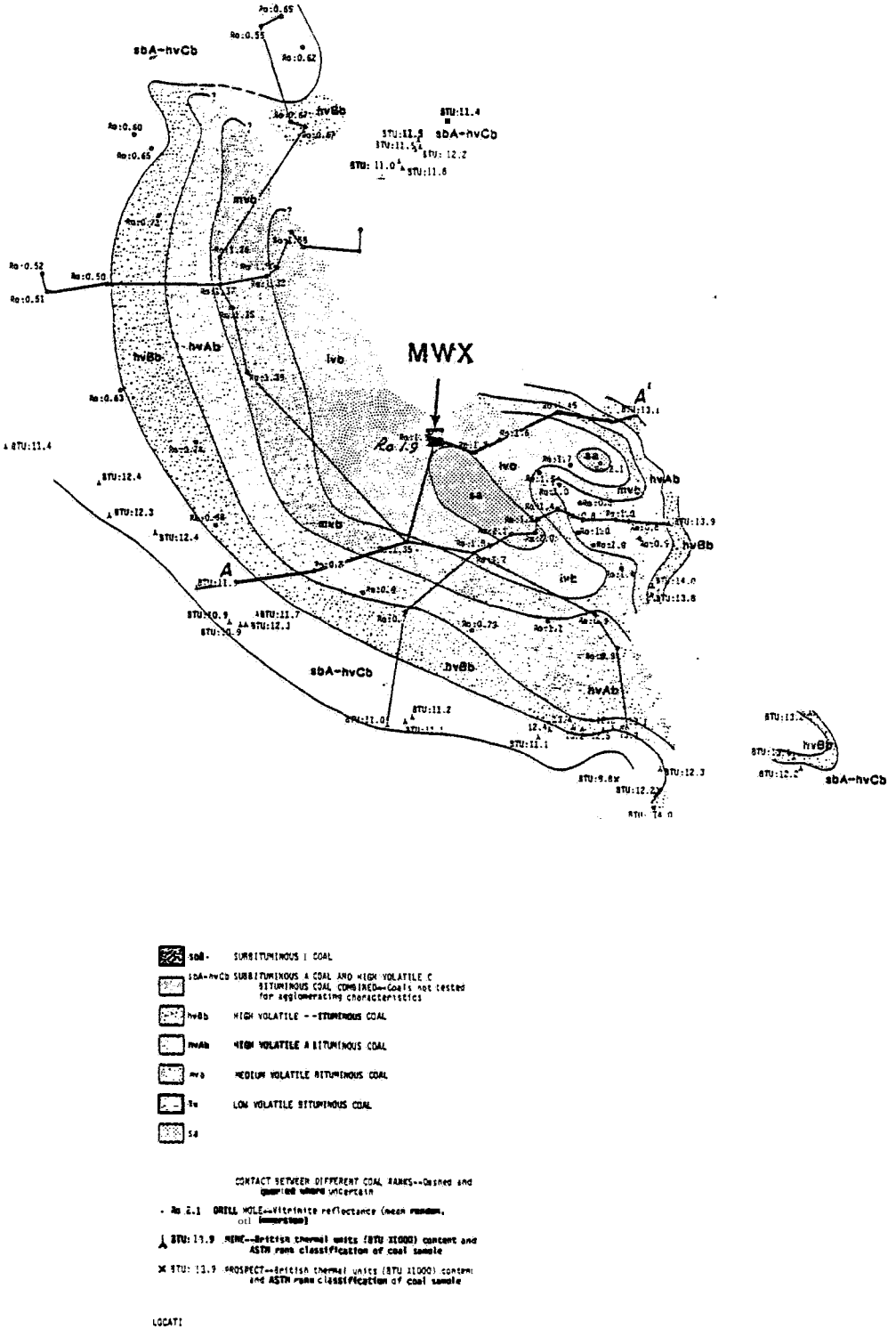


Figure 2.--Map of the Piceance Basin showing coal ranks of the Paludal Zone coal Coal ranks increase in a general eastward direction. The vitrinite reflectance for the Paludal Zone at the MWX site is 1.90%, equivalent to a rank of low volatile bituminous (lvb) coal. Johnson and Nuccio (in press)

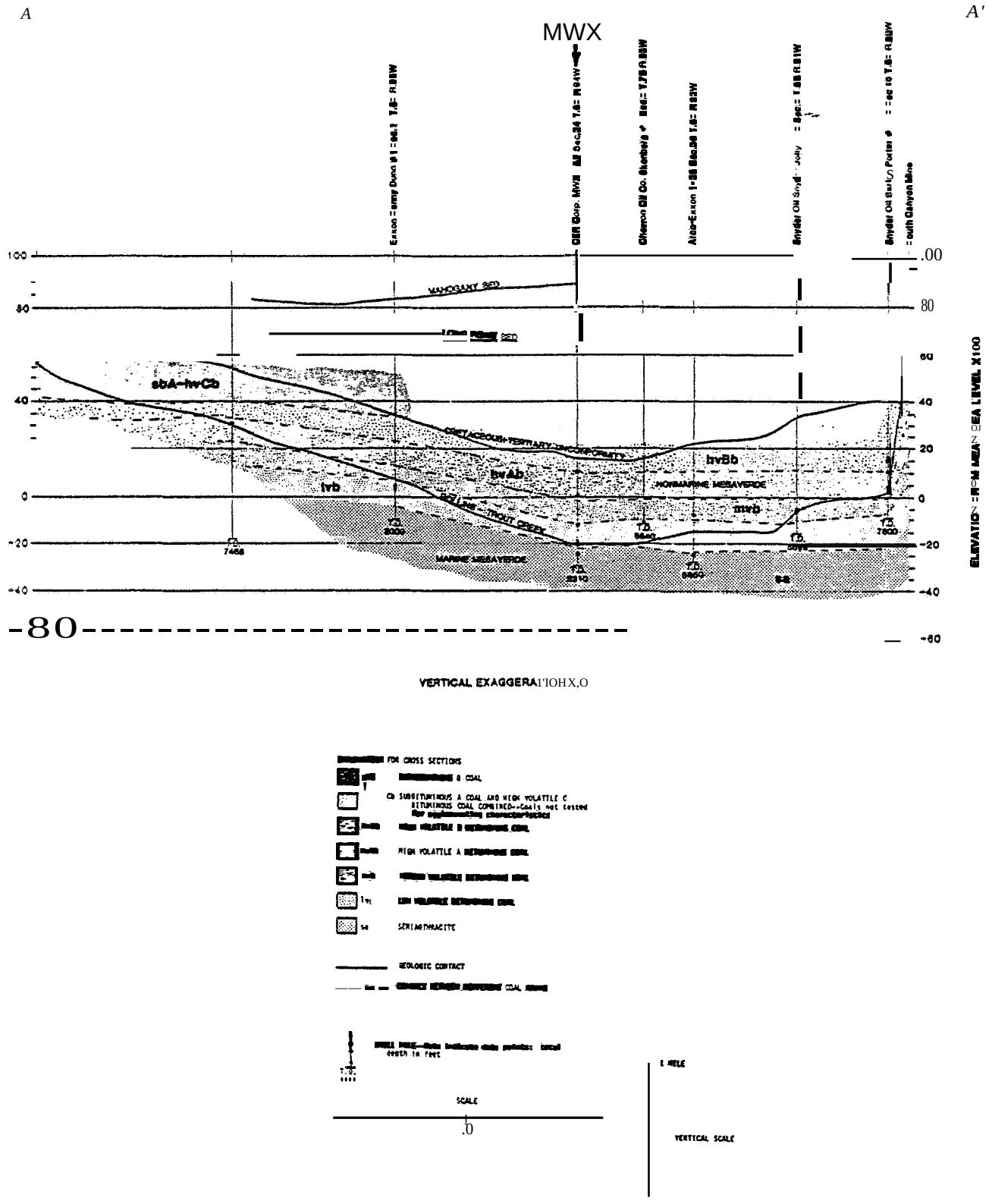


Figure 3.--Cross section A-AI drawn approximately parallel to the Colorado River, in south-central Piceance Basin. Coal rank zones are superimposed on the cross section. The Rollins sandstone Member, top of the Cretaceous, Long Point Bed and Mahogany zone of the Green River Formation are also shown. The onset of gas production is in the high volatile B bituminous (hvBb) zone and increase with depth and coal rank. Johnson and Nuccio (in press).

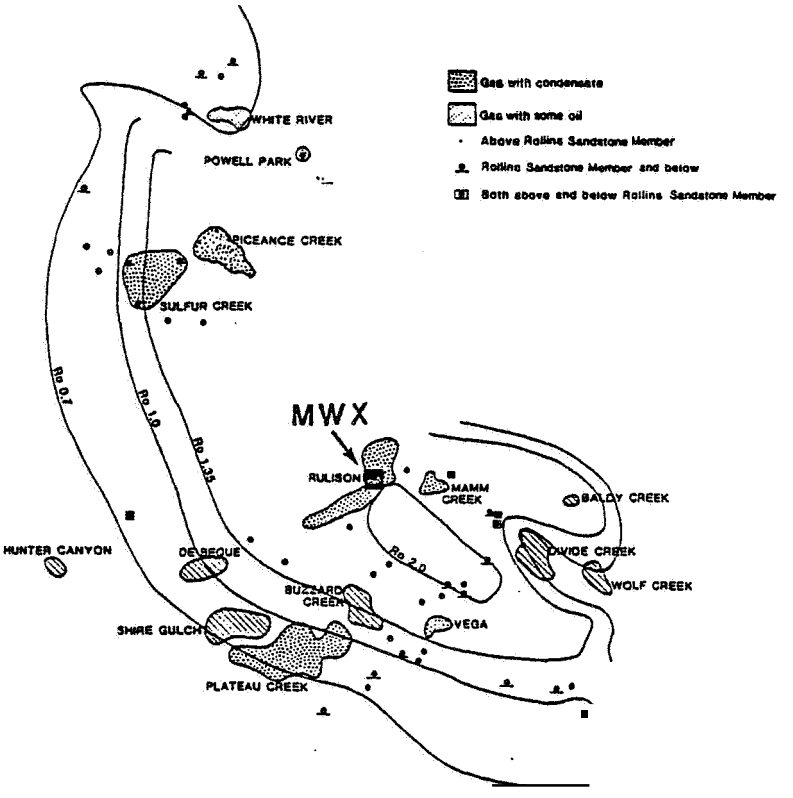


Figure 4.--Map of the Piceance Basin showing fields that produced oil, gas, and condensate from the Mesaverde Group through 1981. 0; 1 and gas producti on is subdivided into production from above or below the Roll ins sandstone Member. Other wells that have tested oil and gas but have not produced, or for which no production f; guresare ava ilabl e are also shown. The Mesaverde Group mainly produces gas, but may contain small amounts of oil and condensate. This map also shows contours of vitrinite reflectance (Ro) values at the Roll ins Sandstone level. The onset of major gas production i in rocks with a Roof about 0.70%. Oil is produced in rocks up to a Ro of .35%, at which point it is thermally destroyed. From Johnson and Nucc 0 (in press).

data. These measurements were then converted to coal-rank. Figure 3 shows the thermal maturation in the vertical dimension through the MWX site and shows increasing coal rank with depth. This type of paleothermal mapping has utility in allowing explorationists to predict the depths and areas where gas (and oil) may be expected to have been generated and the areas and depths at which oil will be thermally cracked to form gas and condensate (see discussion on thermal maturation). Figure 4 is a map of the Piceance basin showing contours of vitrinite reflectance data of the Rollins Sandstone level. The Rollins Sandstone is a marine sandstone above the Cozzette Sandstone and below the paludal (coaly) zone.

$C^{12/C13}$ isotope ratios of gases from MWX and nearby wells by D. D.Rice and C.N. Threlkeld, (1981) as well as $C^{12/C13}$ and $0^{16/018}$ ratios of fracture-filling calcite cements in natural fractures by J. K. Pitman, USGS and Eve Sprunt (in press), have been analyzed. These studies provide some insight into the origin of the gases fracture-filling cements, general temperature, and other conditions (trends), under which the cements (and fractures) may have formed. These data along with a proposed sequence of pore pressure variation have been furnished to SNL for their natural fracture studies.

USGS Studies Under SNL Direction

Two USGS research efforts, surface fracture and vertical seismic profiling (VSP) related to MWX, are under the direct supervision of SNL and the general supervision of the USGS Principal Investigator. This work is being supervised directly by SNLformaximum efficiency, because SNL is the lead research group for the natural fracture analysis and the 3-D seismic and VSP work. E. R. Verbeek and M. A.Grout (1984) have recently published a report (USGS Open-File Report 84-156) on the surface fractures based on measurements made at more than 300 sites. They classified the fractures and compared the surface fracture data with subsurface MWX data. M. W. Lee (1984a,b,) has published two reports on the VSP work. These reports are entitled "Vertical Seismic Profiles at the Multiwell Experiment Site, Garfield Co., Colo." (USGS Open-File Report 84-168) and "Delineation of Lenticular-type Sand Bodies by the Vertical Seismic Profiling Method" (USGS Open File Report 84-265).

RESEARCH METHODOLOGIES, RESULTS, AND UTILITY OF DATA

Regional Setting

One of the major objectives of the USGS geologic program is to characterize the geologic setting of the MWX site. Several regional structural maps of the Mesaverde have been compiled by R. C. Johnson, using standard well-log correlation techniques. Isopach maps also were prepared for the nonmarine Mesaverde so that shallow structural well control could be projected to depth in areas where no deep drill control existed. For example, in order to make the Upper Cretaceous Rollins Sandstone structure map, (Figure 1), shallow Tertiary-Cretaceous structure control was projected on the basis of the isopach map data down to the top of the Rollins in areas where no Rollins well control was available.

Isopachs of Tertiary stratigraphic intervals were prepared to show structural growth after Cretaceous Mesaverde deposition. For example, the areas where Tertiary strata thicken were structurally low at the time of deposition; and areas where Tertiary strata are depositionally thin (toward basin margins), represent paleobighs where gas in Cretaceous rocks would move early in the migration history of the basin. Isopach maps also show structures that should have been local focal points toward which early generated gas would have migrated prior to the permeability reduction accompanying deep burial and reservoir cementation.

Although the USGS has compiled regional iospach data, the detailed aspects of the sedimentology and stratigraphy (sandstone geometry) in the southern Piceance-MWX area have been analyzed by John Lorenz (SNL). Cooperative assistance was provided by Romeo Flores (USGS) relative to sedimentologic interpretation of the MWX core. The USGS has met with SNL personnel in the field for cooperative surface work and participated in the review of some SNL reports. There is no duplication of effort between USGS and Lorenz's work.

Thermal Maturation

In order to improve predictability of the distribution of gas, and predict reservoir pressures and rock stress history in tight reservoirs at MWX

and elsewhere, it is necessary to understand recent research on the origin of gas (and oil) and overpressuring in the Rocky Mountain Region and at MWX. The following discussion is excerpted frolll a report by Spencer to DOE (Jan. 1984).

First, natural gas can be generated by bacteria (biogenic) at low temperature and pressure such as that occurring in the Northern Great Plains (Rice and Shurr, 1980). Second, gas and oil are generated by the thermochemical breakdown of organic matter.

Areas of biogenic gas are usually underpressured. Carbon isotope work by D. D. Rice, USGS, (letters to A. R. Sattler of September 15, 1982 and February 14, 1983) shows that the gas at the MWX site was generated thermally and that some of the gas in the lower part of the MWX drilled section apparently was fo.rmed by the breakdown of previously formed oil that originated from marine hydrocarbon source beds.

There are two types of naturally occuring organic matter that are the main source of hydrocarbons; 1) hydrogen-rich (lipid-rich) kerogen, and 2) woody (low-hydrogen) kerogen. Hydrogen-rich kerogen is most common in marine and lake deposits (shales and siltstones); whereas, the woody type kerogen, typically derived from land plants, is common in continental shales, mudstones, siltstones, and coals. As might be expected, coals are mostly made up of woody kerogen.

Figure 5 shows a generalized diagram of the sequence of generation of hydrocarbons from lipid rich kerogen. This kerogen is referred to as "oil prone" because it goes through a thermal stage where a large volume of oil is generated relative to gas. On continued heating this oil breaks down to wet gas and then to dry gas. When the oil breaks down to gas, a dark pyrobitumin residue commonly remains in the reservoir rock. We described such a residue in the core from the Cozzette in MWX-2 (Spencer letter of August 18, 1982 to D. A. Northrop).

Land plant (woody) matter is the source of most of the gas in tight reservoirs at the MWX site. Woody kerogen is also the source for much of the gas in the Piceance basin in general, and the Wind River, greater Green River, and the dry gas parts of the Uinta basin.

Figure 6 shows a generalized diagram of hydrocarbon generation from woody, "gas prone", kerogen. This figure shows an initial low pressure

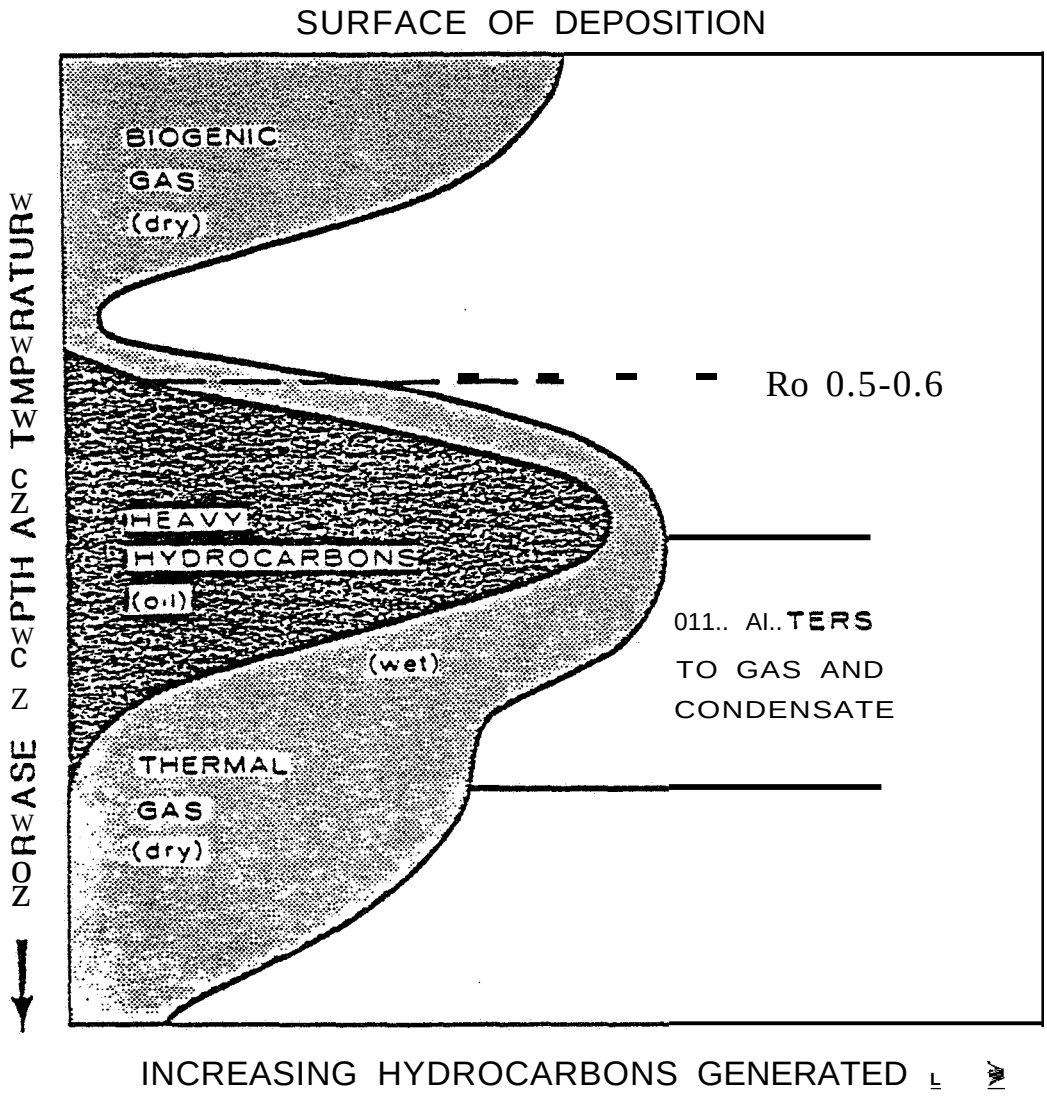


Figure 5.--Generalized diagram showing the sequence of hydrocarbon generation (oil and gas) from hydrogen-rich organic source beds with increasing temperature (and time). Modified from Rice and Claypool (1981).

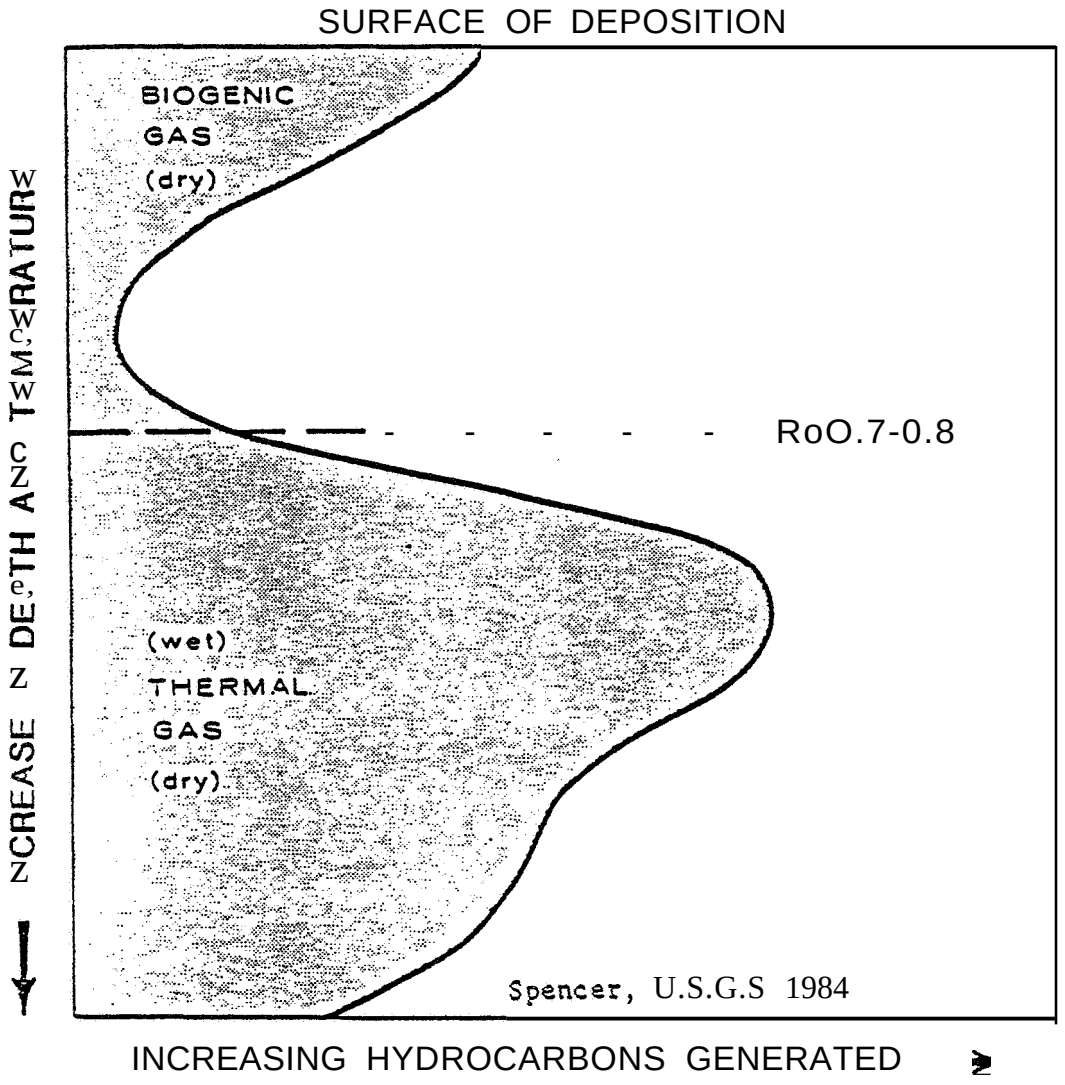


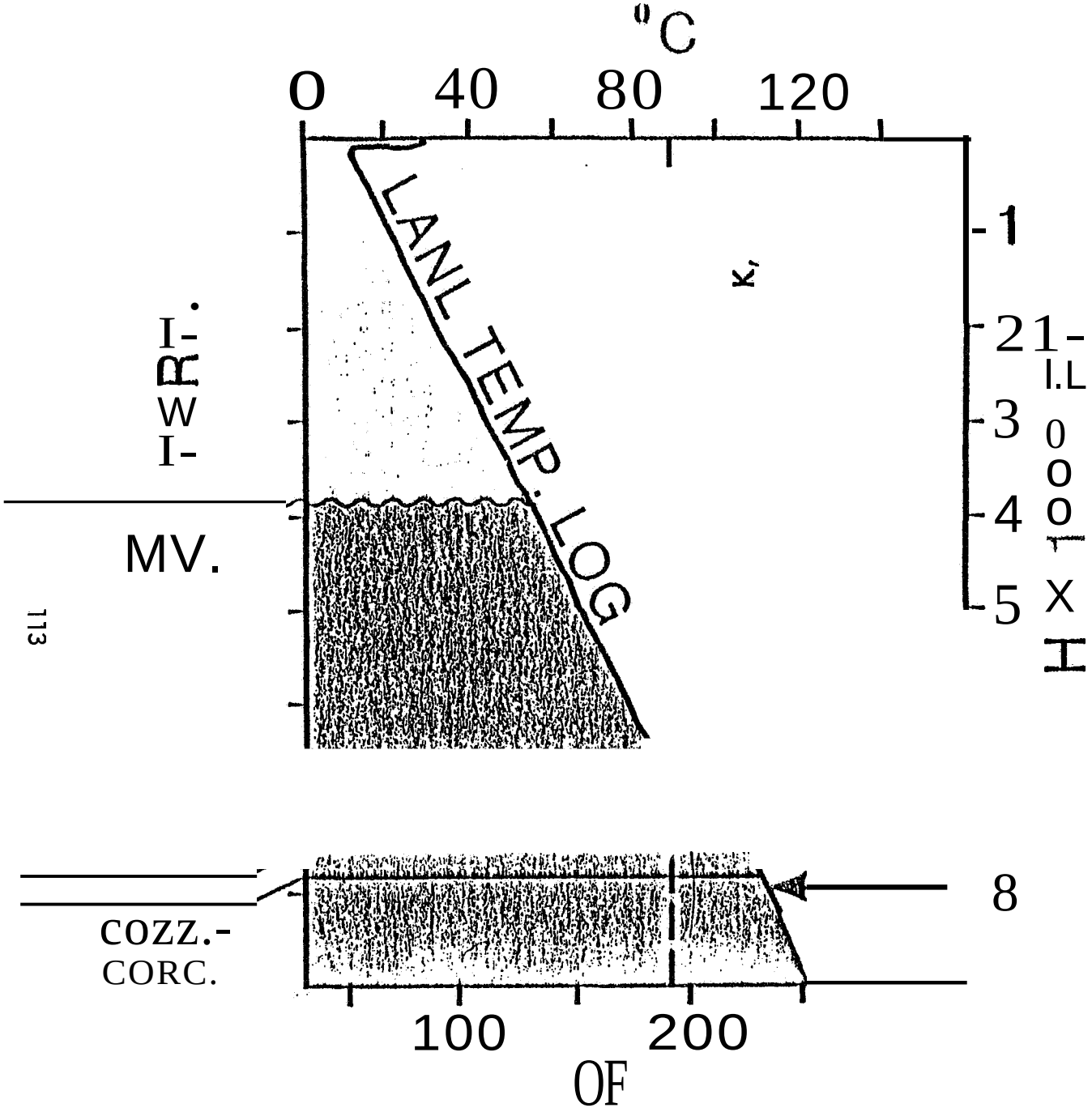
Figure 6.—Generalized diagram showing the sequence of gas generation from land (woody) plant-derived,. gas-prone kerogen with increasing temperature (and time.

biogenic phase, and a later thermal stage. The onset of the main thermal phase of gas generation is thought by some workers to start at a vitrinite reflectance value of about 0.7 to 0.8 reflect.ance in oil (R_o). Others believe it may start at a slightly lower or higher R_o, but in the Principal Investigator's experience the Figure 6 values best fit data from most basins.

Proposed origin of high-pore pressure

Law, Spencer, and Bostick (1980) proposed that overpressuring starts to occur in tight gas reservoirs when the rock temperatures increase'to about 190 to ZOOoF. The overpressuring is caused by the as generated by the heating. The overpressuring continues as the rocks (and kerogen) continue to be heated until the kerogen is largely converted to gas and coaly residue. Because the kerogen goes through a peak or maximum generation phase (Fig. 6), most overpressuring is seen in rocks between 0.7 R_o and about 1.5 R_o. However, in coal-rich intervals the overpressuring (significant gas generation) continues into quite high thermal maturation (coal rank) stages. The reason for this is that organic-rich source beds typically contain only about 0.5 to 5 percent organic carbon; whereas, coals are jaostly organic matter. The organic-lean beds, once past the stage of peak gas generation, can not keep generating volumes of gas at a high enough rate to keep up with "bleedoff" caused by gas migration and diffusion. The coal beds seem to be able to maintain gas generation at a level high enough to maintain a high or abnormally high pore pressure. Obviously, the temperature must remain at least high enough to generate gas (190 to ZOOoF or higher). Figure 7 shows the intercept of the 190°F reservoir temperature from the MWX-1 LANL temperature log, with the significant apparent increase in pore pressure.

The maximum pressures encountered in tight gas reservoirs are at about the fracture gradient of most tight gas reservoirs. This would suggest that the fracture gradient of the rocks is a controlling factor limiting maximum-pore pressure. Meissner, (1978) suggested this pressure-release mechanism for overpressured oil reservoirs in the Williston basin. The estimated pore pressure in the Cozzette at MWX-1 is about 0.81 psi/ft (Branagan and others, 1984) and the fracture gradient for the sandstone is about 0.86 psi/ft. However, more pore pressure and fracture gradient data need to be acquired and analyzed in order to fully understand the pressure-relief mechanism.



MWX#1

TEMP. VSFACIES & OVER-PRESS.

Figure 7.-Lus Alamos National Laboratory temperature log run in MWX-1 showing thermal gradient anomaly about cod ncIdeut with increaoe in mud weights uaed to control reae.rvofr overpressuring. Line showing 190° F point minimum l:, erature to maintain "active" generation aLao sho:

The conclusion is that gas generation causes high pore pressure which is a significant factor in paleorock stress, and may or may not be a significant factor in the actual development of vertical fractures. Differential pore pressure certainly is a mechanism for migration of gas and reservoir liquids. If high-pore pressure can move reservoir liquids, then the movement of these liquids is probably a significant factor in the formation of pore and fracture-filling cements.

Proposed Paleopore Pressure at the MWX Site

Our ability to predict the onset of overpressuring in present-day tight gas reservoirs is improving. However, the maximum amount of overpressure does not seem to be predictable at present. There are many types of data needed, such as; 1) thermal history, 2) reliable present-day temperature data, 3) level of thermal maturation, 4) ability of source beds to still generate gas, 5) organic-richness of the source beds, 6) natural fracture gradient of seals and reservoir rocks as well as their lateral and vertical permeabilities. The DOE research effort at the MWX field laboratory is attempting, for the first time, to characterize these data as well as much other critical information.

The vitrinite reflectance work of the USGS (N. R. Bostick, V. Freeman, and V. F. Nuccio) and Amoco Production Company provided a high-quality vertical profile of thermal maturation at the MWX well. Recently completed regional vitrinite mapping in the Piceance basin by Nuccio and Johnson (1983) helps to place the MWX site in perspective with the rest of the basin.

On the basis of normal burial history, and burial curves prepared by Johnson and Nuccio (in press) coupled with the gas generation diagrams (Figs. 5 and 6) the pore-pressure sequence in the Mesaverde of MWX was probably as follows:

1) Biogenic gas generation (low press., low temp.; Rice and Schurr, 1980)
2) Elevated pore pressure caused by dewatering of sediments (probably continued biogenic gas generation)
3) Increase in temperature create subsurface environment incapable of supporting methanogenic bacteria.

4) Permeability of reservoirs decrease owing to rock diagenesis and compaction. Pore-pressures in low grade coals and lignites in paludal zone may increase.

5) About 50-55 million years ago, onset of oil generation in Upper Cretaceous Mancos Shale marine source beds enclosing Corcoran and Cozzette (Co-Cz) Sandstones, followed by overpressuring due to continued oil generation.

6) Oil migrates into Cozzette stratigraphic trap (e.g. MWX-2 core), overpressuring probably continuing at the Corcoran-Cozzette level.

7) About 48-52 million years ago, initiation of significant gas generation in paludal zone probably causing high pressures. in excess of 0.8 psi/ft. Lateral natural-gas fracturing probably occuring, and possibly some vertical gas-fracturing now occuring. Large gas volumes being generated. Gas migrating by pressure differential and buoyancy. Water is simultaneously expelled from coals (Law and others, 1983) causing a continued increase in paludal zone formation water resistivities (Rw).

8) Continued burial and heating causes critical gas-generation temperature front to move upward in the Mesaverde, charging these reservoirs with gas increasing pore pressures in the upper part of the fluvial Mesaverde.

9) Corcoran-Cozzette reservoirs heated to an R_o >1.35 and oil is volatilized causing additional increase in pore pressure. Organic-rich coals in Paludal Zone continue t.o generate gas and pressure adjacent reservoirs but volume of expelled water is decreasing.

10) Colorado River starting to cut downward toward the present MWX topographic surface, approximately 9 to 10 million years ago causing sediments to cool off. As the temperature in each source bed in the fluvial section drops below 200^{oF} gas generation ceases and pore pressure returns to normal.

11) Present-day; the coastal zone pressure begins to return to normal but the paludal section is still overpressured because of organic-rich source rocks and temperatures >190-200^{oF}. Corcoran-Cozzette interval is still overpressured owing to high temperatures, the effectiveness of the Mancos Shale as a seal, and a low level of gas generation in enclosing shales of the Mancos. The Corcoran Cozzette sandstones

have already been fractured (jointed) and are encLoeed'-Ln shales with a fracture gradient higher than the Co-Cz reservoir pressure (0.81 psi/ft) (Branagan and others, 1984).

Additional refinement, if possible, of the paleotemperature models will be made to attempt to predict the timing and magnitude of paleopore pressures. It is not known if the loss of pressure caused by gas leakage related to tectonic fractures can ever accurately be predicted.

Reservoir Characterization

Geologic characterization. of the reservoir rocks at MWX is one of the major objectives of this research effort. The MWX core provides a unique opportunity to compare detailed petrographic data with a wide variety of other types of data including rock mechanics studies, special core analyses, special well logs, and conventional and special logs.

Petrographic and mineralogic characteristics

The Bendix Field Laboratory has the responsibility for routine description of MWX thin sections and conducts some X-ray diffraction studies of clays. The USGS reviews the Bendix data and provides quality assurance to DOE on this work.

The USGS has state-of-the-art petrographic laboratories and equipment. MWX core is studied using scanning electron microscope (SEM), qualitative and quantitative X-ray studies of whole rock and clays, fission-track anealing studies, fluid inclusion studies, oxygen and carbon isotopic studies of fracture-filling cements, and microscopic studies of natural fractures.

The reservoir rocks at MWX are generally typical of the rock types that contain most of the potential gas resources in the Rocky Mountain basins - most of these rocks are impure sandstones called litharenites, feldspathic litharenites, and arkoses. Litharenites are sandstones that contain dominantly quartz but also have significant amounts of rock fragments derived from the erosion of sedimentary, igneous, and metamorphic rocks. The feldspathic and arkosic rocks also are dominantly quartz-rich but contain significant amounts of feldspar grains.

The reservoir rocks are tight because they have been well cemented by quartz, clay and carbonate that were precipitated after deposition. Some of these rocks may have been conventional reservoirs prior to cementation. The USGS analyzes the reservoir mineralogy and texture and interprets how these factors will affect well log response.

Porosity and permeability character

Work by USGS petrographers has shown that the reservoirs in MWX, are tight because the pores are scattered or relatively isolated through the rock. The pores, typically formed by dissolution of minerals, are .poorly connected by tortuous, ribbon-like capillaries (Spencer, 1983). Many of the pores are filled with secondary clays which were precipitated after deposition. These clay reduce permeability to gas, increase water saturation *(8w),* and lower formation resistivity (Rt).

Relationship of petrography to log analysis problems

Our petrographic studieo do not necessarily "solve" log analysis problems but have helped to identify those parameters which affect log response. This information prOVides some of the data for the design of new log computer programs (developed by G. C. Kukal, CER). These studies also help to explain why certain conventional well logs do not accurately record porosity, water saturation, and other parameters. For example, most of the MWX tight reservoirs have grain densities higher than quartz (2.65 gm/cc). As might be expected, this is caused by the presence of minerals with densities higher than quartz but the petrographic work shows that the abundance of these "heavy" grains varies laterally and vertically, so a density log "matrix" calibration to 2.68 or 2.70 will not uniformly correct porosity readings in all reservoirs. Ideally, a tool should be developed which will measure grain density and constantly make calibration corrections. G. C. Kukal and others are trying different techniques to solve this problem. A more complex logging problem was noted in the petrographic studies of the paludal zone sandstones. Many of these reservoirs have 1) a significant ()1O%) amount of detrital carbonate, 2) clay chips (clasts) and, 3) coal fragments scattered through the rock. The carbonate increases grain densities, while the clay

chips and coal decrease the density. The coal grains appear ascgas-ef Ll.Led porosity on the basis of porosity-log calculations and Rt measurements. The clay chips cause the reservoirs to appear quite shaley.

Another log interpretation problem involves the use of the spectral gamma ray log to interpret types and amounts of clays present in the reservoirs; however, this is not easily accomplished. For example, the potass fum log detects the potassium in detrital rock fragments and potassium feldspar grains as well as potassium in illite, and other clays, in the pore spaces. Obviously the critical factor for gas recovery is the amount of clay in the pore system. We have only mentioned a few of the geologic factors affecting log the interpretation. Much.more research needs to be done in the application of petrographic data to interpretation of present well logs and development of new tools to more accurately measure these complex reservoir parameters.

Isotopes of minerals in natural-fracture cements

In the MWX wells, fractures in the Mesaverde commonly are cemented with coarse-crystalline calcite and with small amounts of quartz, dickite (a kaolin clay), and barite. Carbon and oxygen isotope studies of calcite fracture-fill indicate that fractures were cemented by calcite during hydrocarbon generation, from formation fluids of meteoric (fresh water) origin. Fractures completely cemented by calcite probably act as a barrier to fluid flow at depth; whereas, incomplete calcite crystal growths in the fractures may keep fractures propped open and hence, maintain the increased permeability produced by natural fracturing. Very little information is available in the literature relative to isotope studies of fracture-filling cements. Cemented fractures in the MWX well, as well as other fracture cements in the basin, provide a unique opportunity to conduct isotopic studies of the origin of natural fractures in tight gas reservoirs.

FUTURE RESEARCH DIRECTIONS

There are several areas of research that we believe should be pursued in the near future to advance the state-of-the-art of enhanced recovery of gas from tight reservoirs.

Formation Damage

The USGS work to date indicates that formation damage, in certain tight reservoirs, can be a major obstacle to enhanced gas recovery. It should be noted that this conclusion is not well accepted by many workers. However, interpretation of the potential for formation damage is based on extensive studies of tight reservoirs, not only at MWX, but elsewhere. Formation damage can occur in several ways, 1) liquid imbibition, 2) migration of fines, 3) swelling of clays, unbroken gels, 4) fines caused by abrasion of proppant and formation during fracing, etc. More research is needed to prove or disprove the effect of the formation damage question.

Reservoir Clays

More research is needed in the area of determining the volume of clay in tight reservoirs. Clay volumes are critical to many, but not all, log analysis programs. The spectral gamma ray log is one approach, but on the basis of USGS petrographic work at MWX and elsewhere, we do not know enough about the relative radioactivity of different clay minerals. In addition, some of theMWX reservoirs contain sericite in the rock matrix, and mayor may not contain illite. Both minerals have a strong potassium (spectra) gamma ray response. The matrix sericite is non-damaging but the pore filling illite is a major barrier to gas flow and affects (lowers) formation resistivity.

New and innovative research is needed to differentiate response of clays in pores versus apparent (and real) clay in the matrix.

Mineralogic· studies

We plan to study specific mineral assemblages identified in the MWX wells in detail and relate their origin and occurrence to temporally equivalent rocks in other areas of the Piceance basin. Such studies should be helpful in determining the distribution of low permeability reservoir rocks at other localities that may have gas pootential. Comparisons can also be made with the same age rocks in other basins, particularly the Uinta basin in Utah and the greater Green River basin in Wyoming and Colorado.

Fission Track Annealing

The USGS has several world experts on fission track anealing (FTA). This technique is used to gain insight into the thermal history of rocks. Vitrinite reflectance can tell the approximate maximum temperature to which rocks have been subjected and FTA can determine the approximate time since the rocks were cooled through certain measurable temperatures. Such studies should be useful for integration into the stress history of the basin. A few MWX samples have been studied by a student at Southern Methodist University.

Fluid Inclusion Studies

Fluid inclusion studies are useful to tell the temperature at which minerals were precipitated or crystallized from formation waters. Many of the natural fractures in the MWX wells have fracture lining and filling calcite cements. Fluid inclusion studies have the potential for determining at what temperature the cements were emplaced. This information, coupled with the paleotemperature studies by Nuccio and Johnson, should further refine the research on natural fractures by SNL and indicate if the natural fracturing was, or was not, asssociated with the development of overpressuring noted in the earlier discussion.

Core Petrography to Core and Log Analysis Correlation

The USGS and Bendix petrographic data are being compiled in a computer file as our time and funds permit. We intend to run statistical correlations of different parameters to see if certain assumptions can be made relative to core and log analysis. This should also help to serve as a cross check on the core analysis results. For example, IGT special core analyses showed that the MWX Paludal sandstones are less compressable (stronger) than most of the other reservoirs. Petrographic study showed these rocks have higher percentages of dolomite than most of the other rocks. The dolomite in the rock 'fabric appears to cause the rock to have increased strength. Log analysis, to core correlations would be accomplished in cooperation with the CER log analysis research.

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TITLE: SEISMIC INVESTIGATIONS OF THE MULTI-WELLEXPERIMENT SITE

ORGANIZATION: SANDIA NATIONAL LASORATORIES

PRINCIPAL INVESTIGATOR: CRAIG A. SEARLS

PERIOD OF PERFORMANCE: CONTINUING

CONTRACT OR PROJECT FUNDING: PART OF THE MULTI-WELL EXPERIMENT AT AN APPROXIMATE 0.5 FTE RATE

Sandia Laboratories

MWX SEISMIC PROGRAM GOALS

- DETERMINE THE GENERAL CHARACTERISTICS OF GAS PRODUCING HORIZONS
- DETERMINE THE EXTENT OF FRACTURE SYSTEMS
- DETERMINE THE ROCK PROPERTIES NECESSARY FOR FRACTURE DIAGNOSTICS

SEISMOLOGY

- THE ACOUSTIC WAVE IS MODIFIED BY PROPERTIES OF THE ROCK THROUGH WHICH IT PASSES

- REFLECTION SEISMOLOGY LOCATES CHANGES IN SEISMIC IMPEDANCE

- ANALYSES ARE DIRECTED TOWARD RECOVERING THE CHARACTERISTICS OF THE EARTH

SEISMIC PROGRAM AND OBJECTIVES:

Sandia Laboratories

A HIGH RESOLUTION THREE-DIMENSIONAL SEISMIC SURVEY

- -TIME POSITION OF REFLECTORS
- -TOPOLOGY OF REFLECTORS
- - AREAL EXTENT OF REFLECTORS

VERTICAL SEISMIC PROFILE OF SITE WELLS

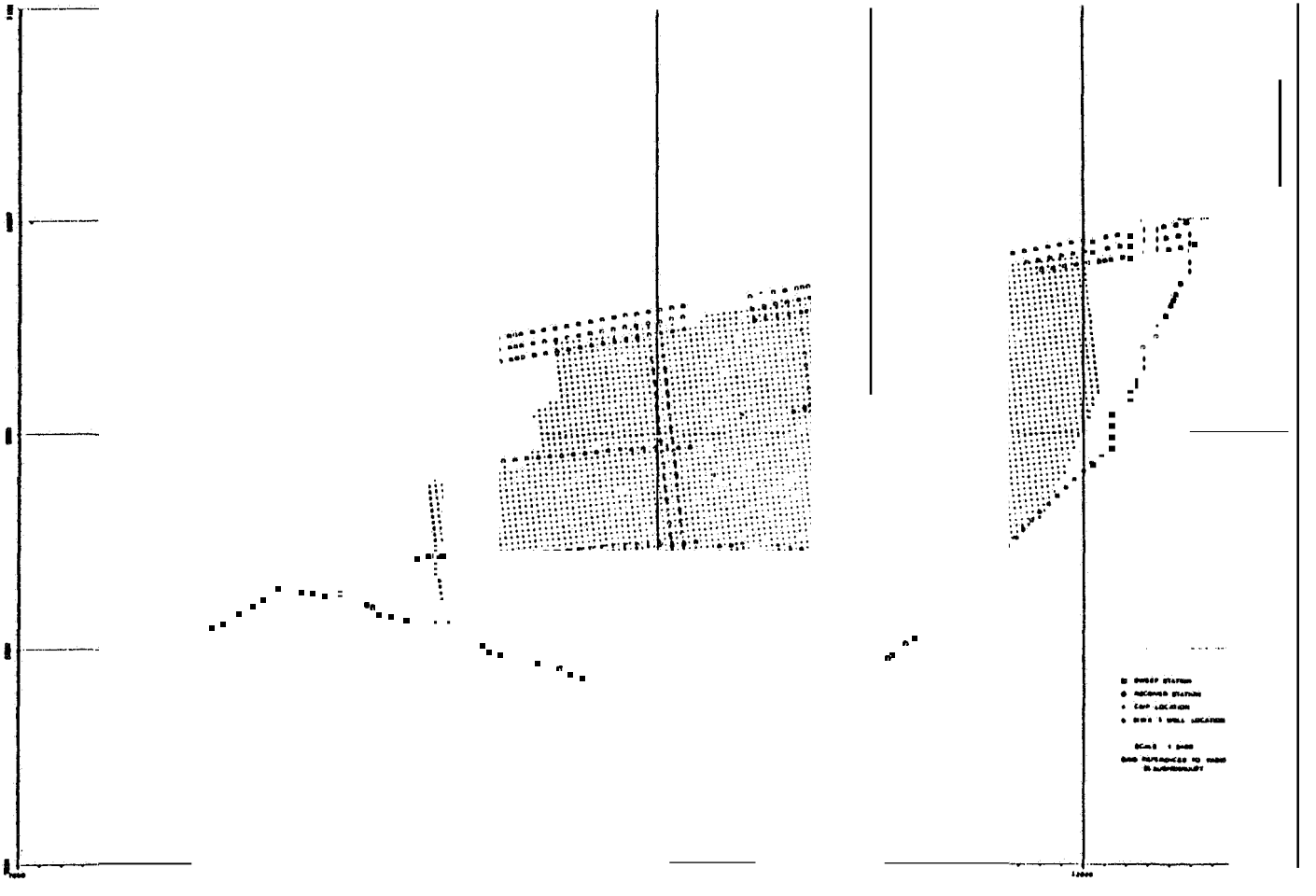
- -DIRECT TIE BETWEEN REFLECTiON TIME AND DEPTH
- -DIRECT COMPARISON OF SEISMIC DATA WITH WELL LOGS AND CORE PATA
- • BULK ROCK PROPERTIES OF REGION SURROUNDING WELL
- - EDGES OF DISCONTINUOUS BEDS PIERCED BY WELL

SEISMIC PROGRAM EXPENDITURES (K$)

Sandia Laboratories

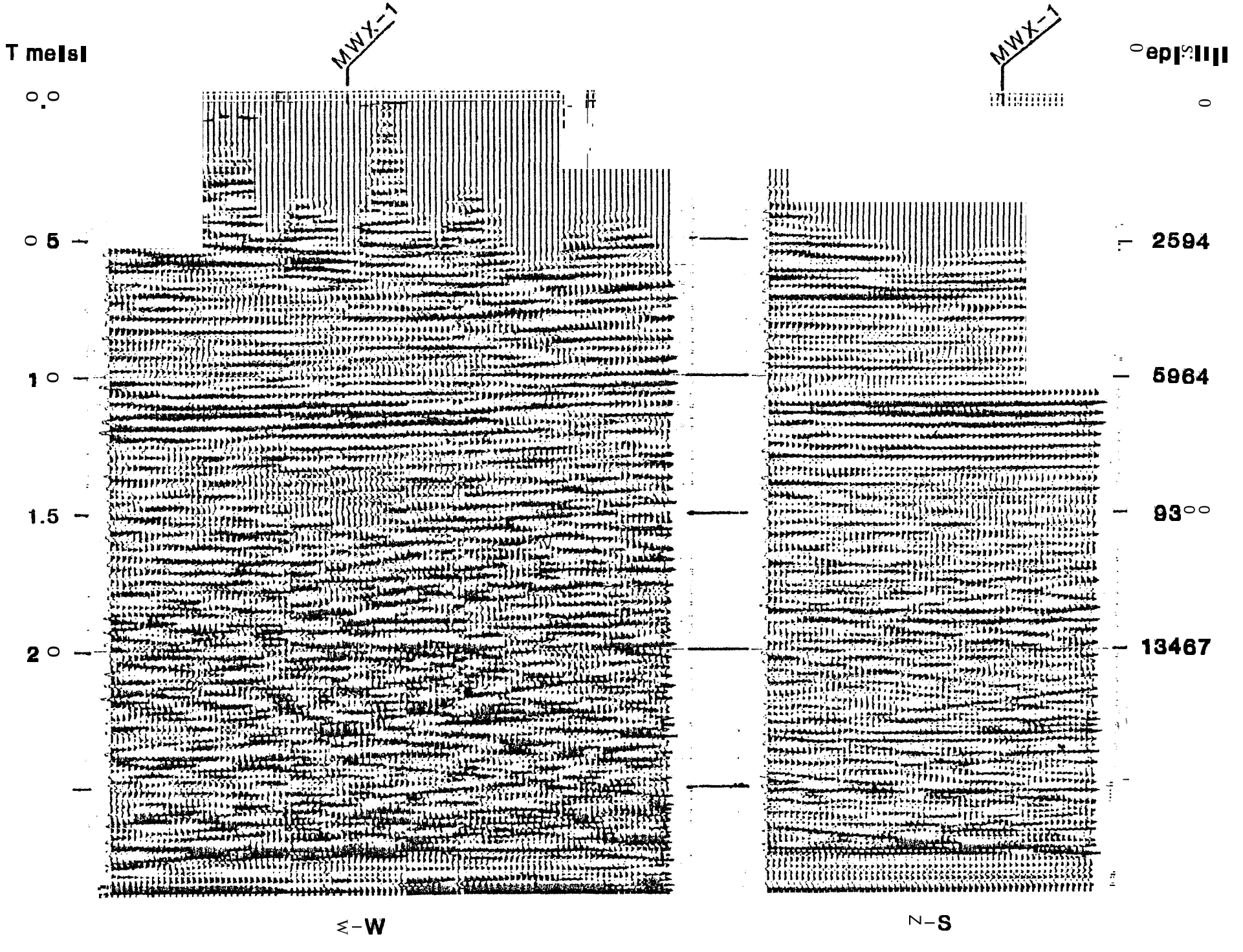
THREE DIMENSIONAL SURVEY:	
FIELD & INITIAL PROCESSING	240
DATA REPROCESSING	80
VSP SURVEY (WELLS # 1 & #2)	45
EXTENDED VSP (W·ELLS #2 AND #3)	162·

WESTERN GAS SANDS PROJECT, RIFLE 3 D STUDY
SURVEY DATA, SHOTS, RECEIVERS, AND WELL



THREE DIMENSIONAL REFLECTION SEISMIC DATA ANALYSIS

- SORT OATA INTO CMP BINS
- STACK THE DATA TRACES TO THEIR TRUE POSITIONS
- CORRECT FOR RESIDUAL STATIC TIMING ERRORS
- MIGRATE THE REFLECTIONS
- CREATE TIME SLICE DISPLAYS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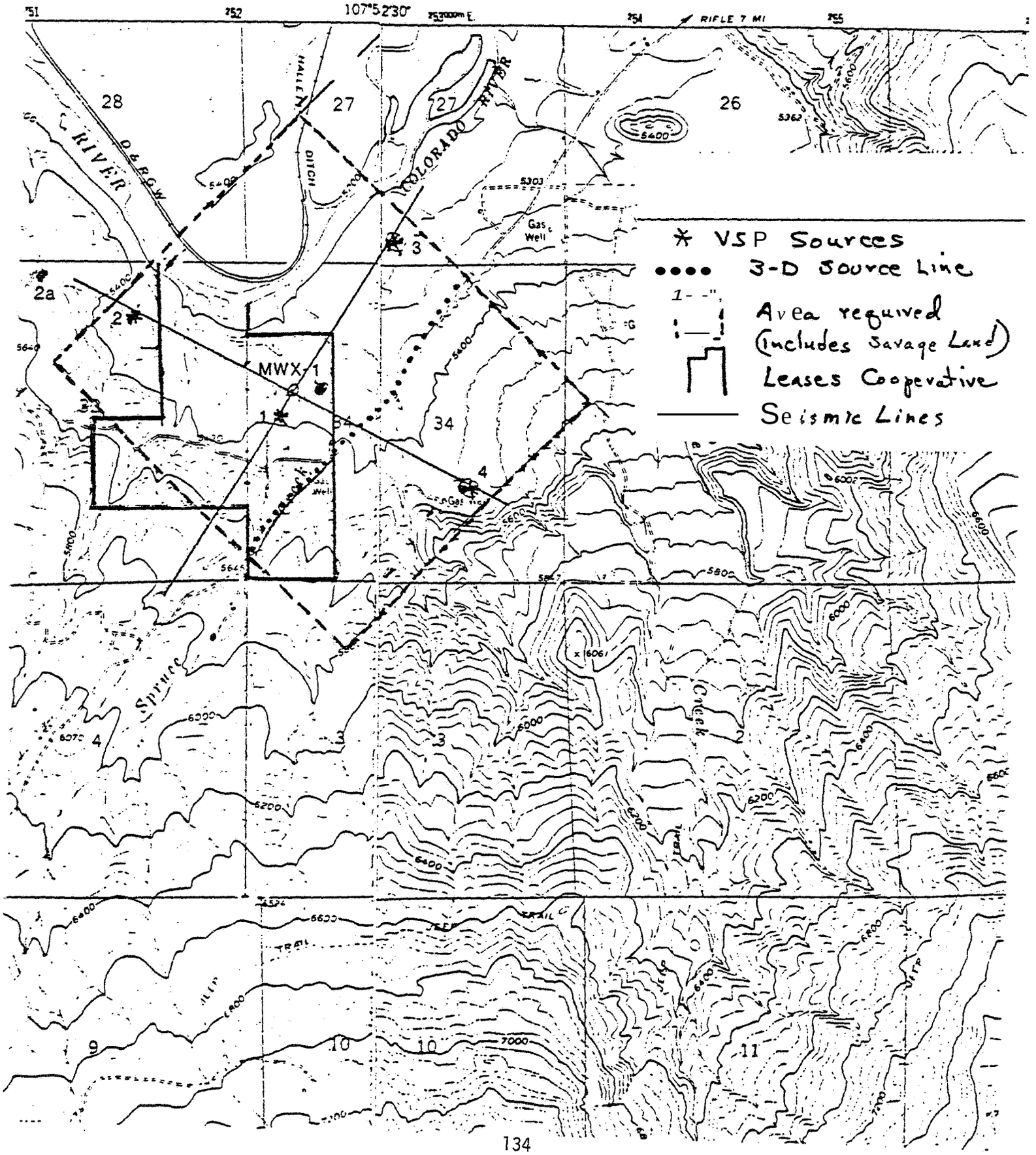
1192 ms

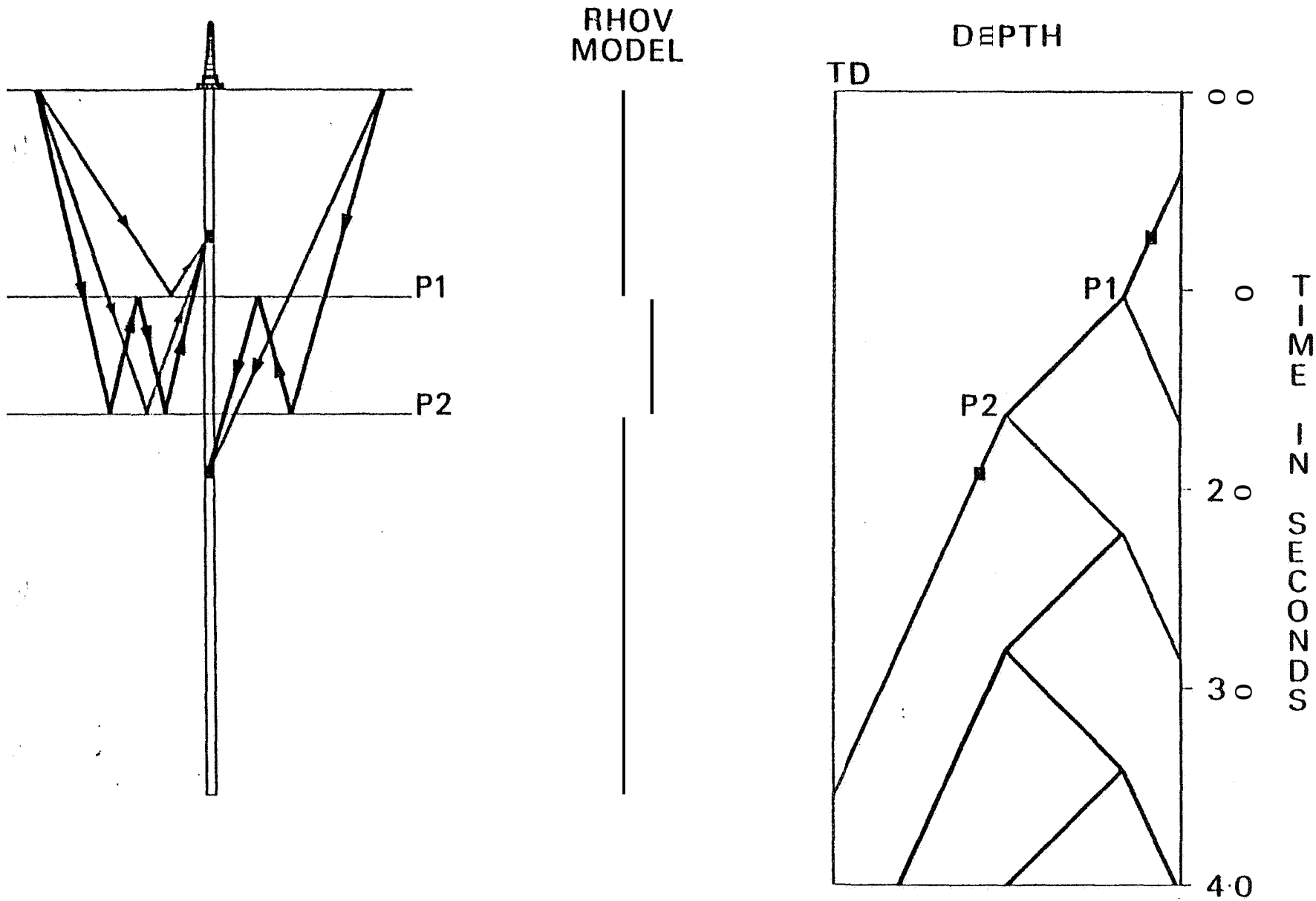
THREE DIMENSIONAL SEISMIC DATA REPROCESSING

- Self Consistant 3-D Statics
- True Amplitude Processing
- Interactive Attribute Processing

RULISON QUADRANGLE
COLORADO-GARFIELD CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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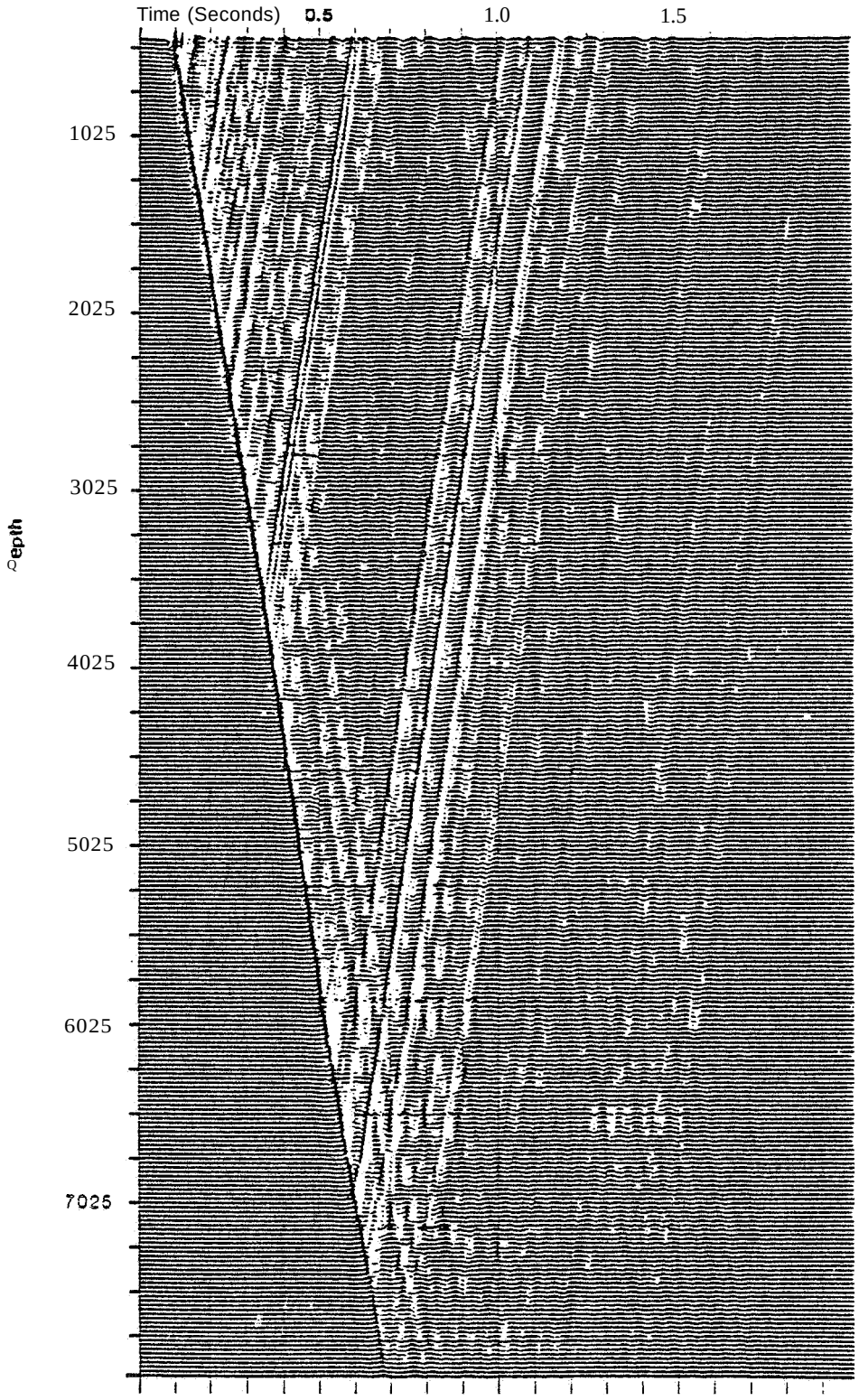
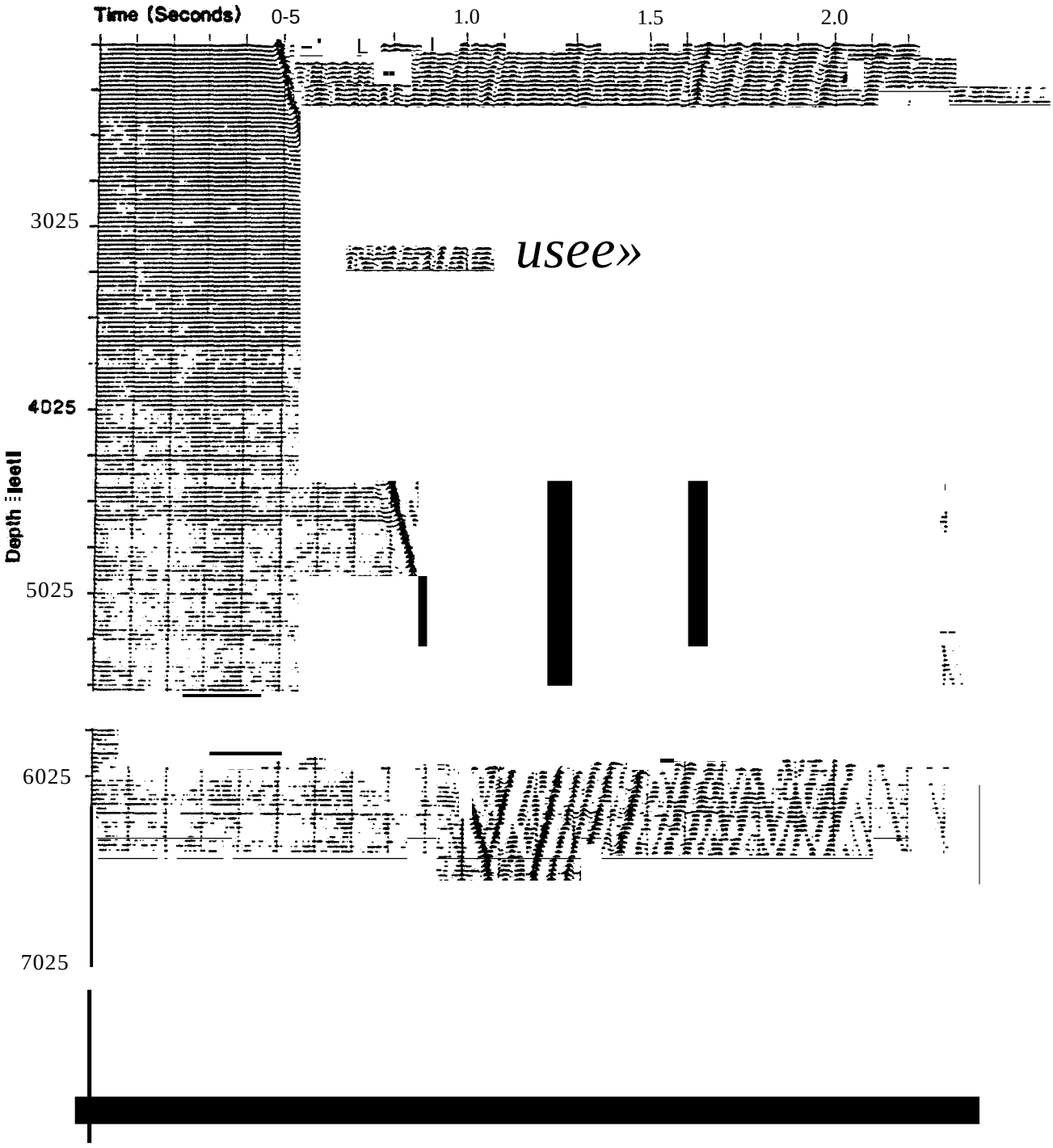
TIME IN SECONDS

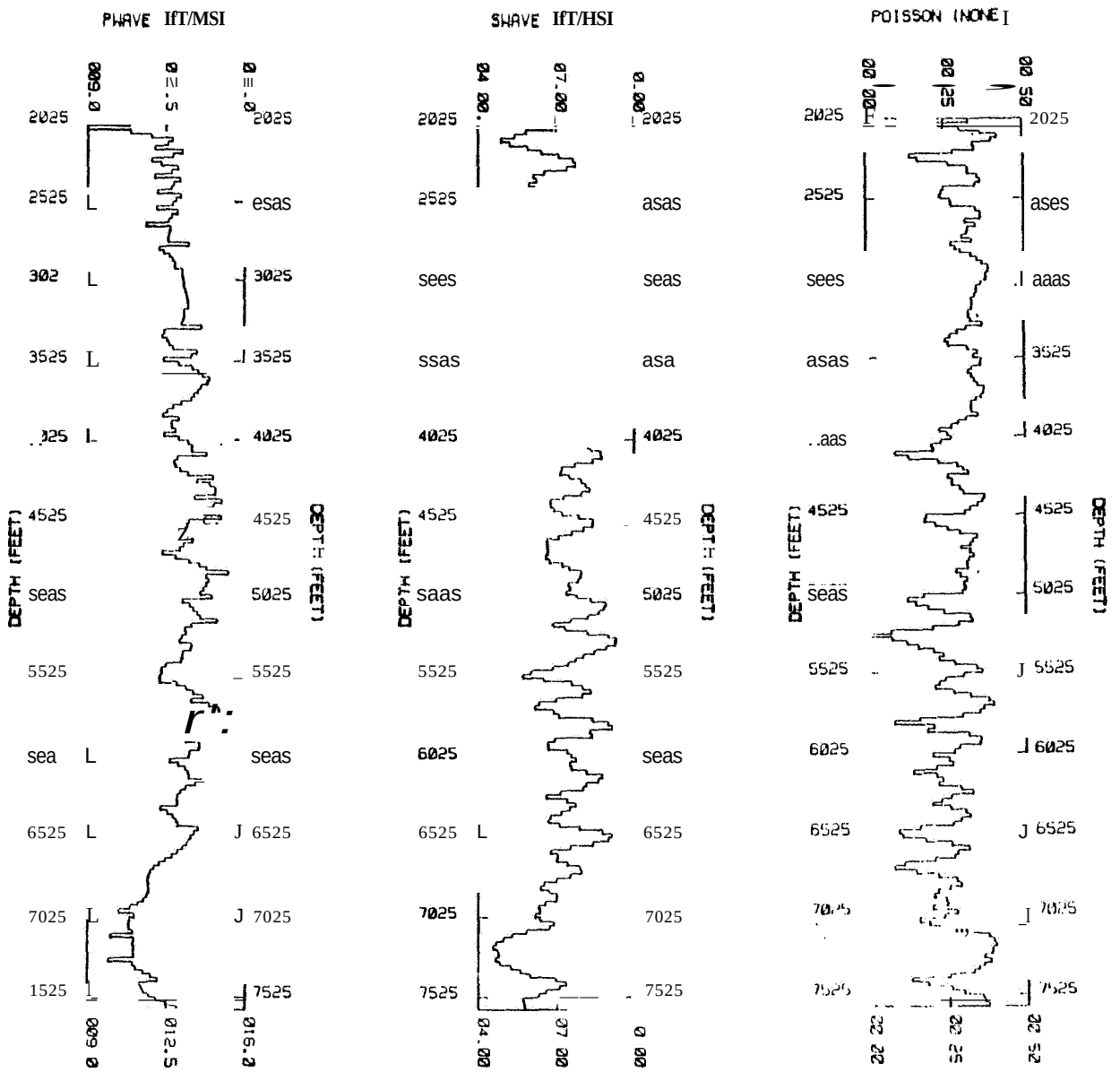
Vertical motion VSP's for the two wells at the
Multi·Well Experiment site after processing

Well #2



Shear motion (SH) VSP for well #2 using the far offset source pcsltlon.

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6525
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7525

EXTENDED VERTICAL SEISMIC PROFILE

- Large Source Offset
- Multiple Source Azimuths
- Simultaneous Borehole and Surface Data Acquisition
- Lateral Stack for Identifying Reflector Edges

SUMMARY AND CONCLUSIONS

Sandia Laboratories

- THREE DIMENSIONAL SEISMIC SURVEY
  - DATA UTILITY IS LIMITED
  - SOMEINFORMATION ABOUT LENS MORPHOLOGY MAYBE OBTAINED THROUGH ATTRIBUTE ANALYSES

- VERTICAL SEISMIC PROFILE
  - PROVIDED GOOD VELOCITY INFORMATION
  - DEPTH LOCATION OF REFLECTORS WAS DETERMINED
  - CAN PROVIDE INFORMATION ABOUT LENSES AWAY FROM THE WELL
  - MAY PROVIDE LENS ORIENTATION THROUGH MODELING

FUTURE WORK

- Improved 3-D Survey of Site
- Shear Wave Survey of Site
- Forward/Inverse Modleing of Seismic Response

Crosswell Acoustic Imaging Project

June 1984 Review

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Project Performance Period	October 1983 - June 1984
Funding Level, FY84	$229K

ABSTRACT

The Crosswell Acoustic Imaging Project underway at Los Alamos National Laboratory, is supported by the DOE Unconventional Gas Recovery Program and the Multi-Well Experiment. Research is directed towards increasing understanding of the structure and properties of tight gas sands through use of crosswell acoustic imaging techniques at the Multi-Well site.

The Project has completed three quarters of activity. The report, intended for presentation to the Peer Review of Unconventional Gas Recovery Research, on June 26-28 in Rosslyn, Virginia, provides an overview of research objectives, tasks, progress, and accomplishments.

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Fig. 4. Relative Attenuation and Average Velocity of Scans in the Coastal Zone

Fig. 5. Propagation Path of Signals Transmitted Between Wells in Waveguiding Structures

Fig. 6. Effect of Limited-Aperture Viewing on Image Distortion

Fig. 7." Reconstructions of Simple Geologic Structures Using Average Velocity Starting Image

Fig. 8. Reconstructions of a Simplified Version of Sattler's Stratigraphic Cross Section

Crosswell Acoustic Imaging Project

June 1984 Review

Overview

Objectives. The Crosswell Acoustic Imaging Project (CAIP) supports the work of the Multi-Well Experiment through the application and continued development of downhole acoustic techniques for examining rock situated between the MWX wells. Specifically for the current contract period, the objectives of CAIP are (i) to provide infonnation relevant to the structure and properties of the Coastal Zone rOCKS through the analysis of crosswell acoustic data in support of the Multi-Well Experiment and (ii) to develop, validate and apply tomographic methodology for the tWO-dimenSional image reconstruction of the acoustic velocity structure between wells.

Crosswell Acoustic Measurements. Crosswell measurements entail the detection, by a sensor positioned in one well, of signals generated by a suitable acoustic source located in a second well. Locking-type geophones and explosives have generally been used as sensor and source, respectively. When using geophones and explosives, crosswell measurements are extremely time consuming. Geophone locking, explosives handling, and multiple trips are required for the acquisition of relatively few signals that are often insufficient to define between-well structures.

A Los Alamos adaptation of the commercial acoustic 1oggin9 tool has removed the historical inefficiency in making crosswell measurements. The Los Alamos borehole tools are centralized, non-locking, and rapidly moved. Ultrasensitive piezaelectric and energetic magnetostrictive transducers are used for sensor and source, respectively. Figure 1 shows a typical set of crosswell measurements. In operation the sensor lalternately referred ta as the

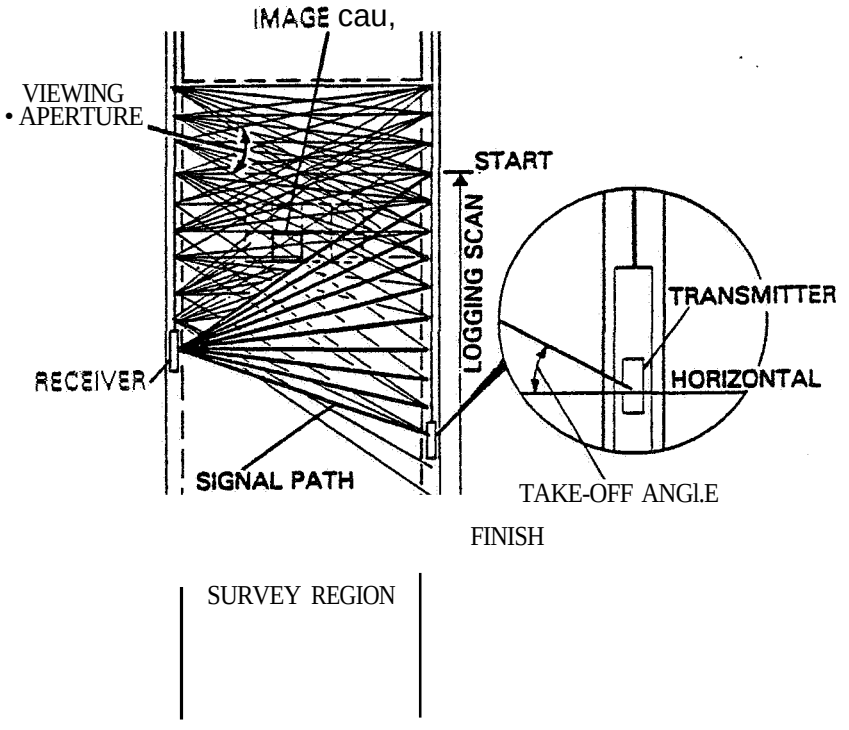


Fig. 1. Crosswell Acoustic Survey

receiver) is held stationary, while the source (the transmitter) is moved 100 ft/min from a position above to a position below the sensor depth in the adjacent well. This operation, which we call a scan, is repeated over and over with appropriate overlap in studying a reservoir strata and constitutes a survey of that strata. Using the Los Alamos tools, the Coastal Zone at the Multi-Well site was surveyed in 1982 under contract to Sandia National Laboratory. During 14 hours of in-hole measurements, 36,000 signals transmitted between wells MWX-1 and MWX-2 were acquired. The wealth of data so obtained makes tomographic and high-resolution acoustic interpretations possible for the first time.

Background - The Multi-Well Experiment and CAlP. Means for investigating rock beyond several well bore radii of gas wells are few. The principal seismiclacoustic methods are: vertical seismic profiling (VSP), 3-D seismic surveying, and crosswell acoustic measurements. While the first two methods are primarily exploration tools useful in characterizing the geologic setting and gross structure of the Multi-\ole" site, the 1ast is a 1imited-range research tool particularly suited to the "tebnratory" formed by the closely spaced MWX wells, Crosswell measurements, because they can be made in situ, have an ultimate resolution 20-100 times better than methods requiring surface sensors and/or sources. The availability of the third well at the Multi-Well site enables unambiguous three-dimensional information to be extracted from crosswell measurements. Thus for the particular case represented at the Multi-Well site, crosswell measurements in addition to being accomplished in situ augment VSP and 3-D seismic interpretation by providing significantly higher resolution data than otherwise possible.

In spite of the broad scope of measurements possible using crosswell methods, the CAIP effort is directed only towards developing the means for extracting specific information for the Multi-Well Experiments. The information in turn may be used by the MWX staff for the planning, analysis, and evaluation of hydraulic stimulations of gas-bearing formations. The questions addressed by CAIP work on the Coastal Zone include:

> Are specific sands that are assumed to be stratigraphically continuous or contiguous between wells on the basis of geophysical logs, in fact so? Are they faulted? Where does a sand clearly represented in only one well, terminate between wells? Do isolated sand channels passing between wells but not penetrated by either, exist? Where? At what depth should geophones be placed to best monitor and map locations of rock failure that occur during hydraulic stimulations of gas-bearing formations? Can overpressurized and/or undersaturated sands be readily identified using crosswell data?

Project Elements, Task Statements, and Schedule. CAIP activity is divided into three principal project elements: (1.0) One-Dimensional Analysis, (2.0) Two-Dimensional Analysis, and (3.0) MWX Field Measurements. The task statements and completion schedule for each element are given in Appendices A and B. Project personnel are listed in Appendix C.

One-Dimensional Analysis. Tasks in the first project element concentrate on extracting line-of-sight information from signals transmitted between wells. For example, a particular discontinuous change in waveform within a scan may indicate that an open fracture exists within the scanned depth interval. Even though the depth at the detected fracture is approximately

known, the lateral position of the fracture between wells cannot be determined. However, knowing that the fracture exists is important. Tasks in thts element emphasize conventional processing and analysis prevalent in contemporary seismology, tend to be accomplished with few man-months of effort, and more or less continually provide new infonnation. The interpretation of these data radically challenges our understanding of the Coastal Zone.

Two-Dimensional Analysis. The objective of the second project element is directed toward extracting the two-dimensional velocity structure from overlapping scans based on techniques of algebraic reconstruction tomography (ART). Although interest in ART spans three decades in the medical and engineering sciences, the use of ART in geophysics is relatively new. To be useful for gas sands research and other geophysical applications, however, the state-of-the-art of a relatively unstudied class of tomographic problems, limited-aperture tomography, must be substantially advanced. CAIP activity in this project element consequently requires the development and testing of limited-aperture algorithms, the assembly of all veloeity determinations made in the Coastal Zone, a singularly huge computatianal reconstruction of the Coastal Zone velocity structure, and interpretations of the result. In comparison to one-dimensional analysis, the two-dimensional analysis, although requiring roughly the same level-of-effort, is a year-long pioneering research activity which is extensive in scope integrating theory, code development, and measurement.

MWX Field Measurements. One anticipates that since there is]ittle experience in making crosswell measurements, substantial improvements in survey design will be indicated by work in this area, particularly as related to 1imited-aperture tomography. Furthennore, the availability of MWX-3 as well as the changing requirements and sophistication of Multi-Well Experiment

Tasks make remeasurement of the Coastal Zone highly advantageous. The third project element meets the need for a higher resolution, more comprehensive survey of the Coastal Zone.

Cost Effectiveness. The principal capital assets required for CAIP (two wireline logging trucks, recording facilities, acoustic tools, mini- and mainframe computers, and software) were assembled at Los Alamos over the course of the 1ast six years in support of DOE Geothennal Programs at a cost substantially in excess of this year's total MWX Project budget. These resources are available for essentially a users fee representing approximately 30% of CAl? costs. The terms of use are extremely favorable. If the MWX field measurements planned *for* July were supported under a contract to a commercial company, even assuming the required downhole tools were available, price schedule costs would exceed the Los Alamos cost by a factor of 3, $45k versus $135k.

Reporting. Written progress reports are provided to K.-H. Frohn at Morgantown. Project reviews were given at Morgantown in January and April and at the MWX Advisory Panel Meeting at Sandia in February.

Project Progress and Accomplishments

The following sections, identified by task, are intended to highlight CAIP progress and accomplishments in the nine months since the Project's inception rather than provide a comprehensive technical review.

1.1 Coastal Zone 6200..6600

Crosswell Acoustic Velocity Log and Pattern Recognition. The survey '82 of the Coastal Zone consisted of partially overlapping scans with both the receiver depth and the starting depth of a 240-ft transmitter run incremented lO-ft between scans. Thus, wh;le the receiver depth is different for each scan in the survey, a substantial portion (23/24ths) of each transmitter run is repeated. A convenient format for assembling the velocity information of the survey data is a representation that we refer to as the Crosswell Acoustic Velocity Log (CAVL), in which the velocity of signals transmitted between wells is plotted versus transmitter and receiver depths, respectively. Two sections of the CAVL are shown in Figure 2.

The principal sands in the Coastal Zone appear on the CAVL as smooth, uniformly higher-than-average velocity intervals. Those intervals are thicker and more homogeneous than one anticipates from a study of the Scnlumberger Sonic Logs.

Scans assemb1ed in the CAVL format enable patterns of veloeity, characteristic of simple but nonetheless important g.eo1ogic structures, to be identified should they occur between wells, The structure and velocity patterns that we have studied are shown in Figure 3. Those structures are: (1) a sand continuous between wells, (2) sand penetrated by on1y one well and terminating between wells, (3) a sand present between wells but not penetrated by either, (4) two sands in the same depth interval, each penetrated by a different well,

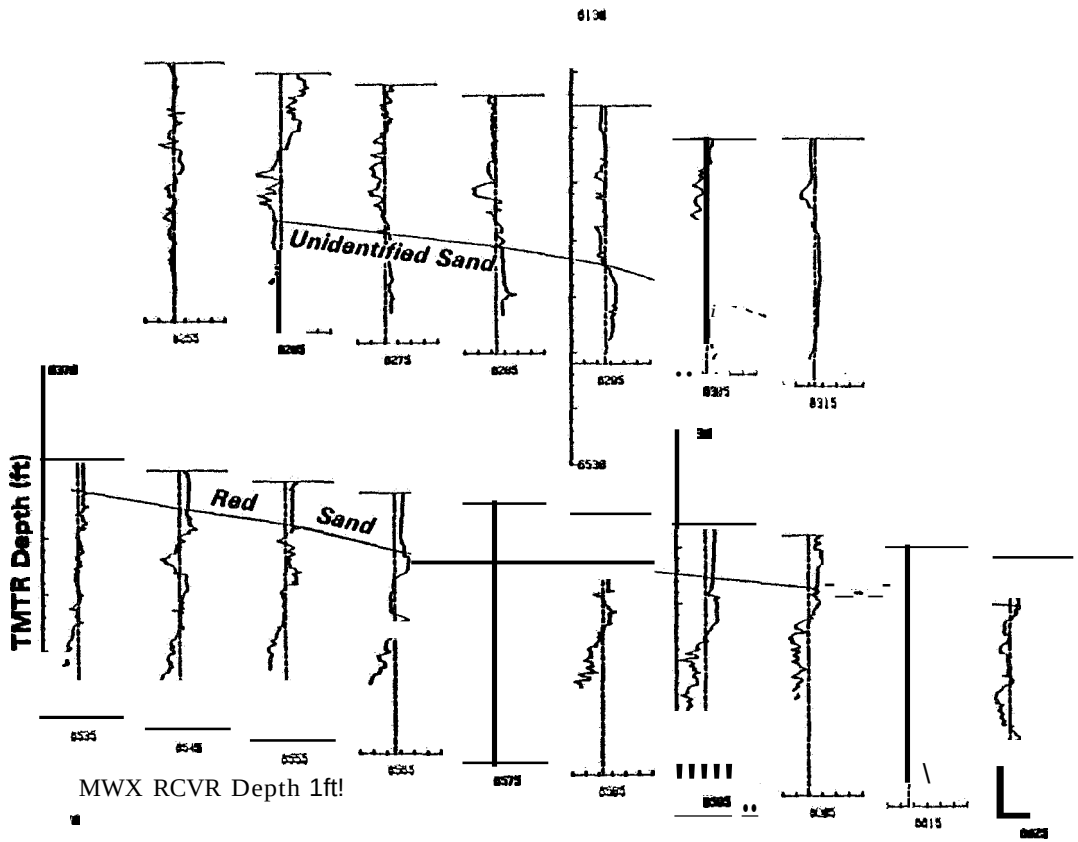


Fig. 2. Portions of the Crosswell Acoustic Velocity log

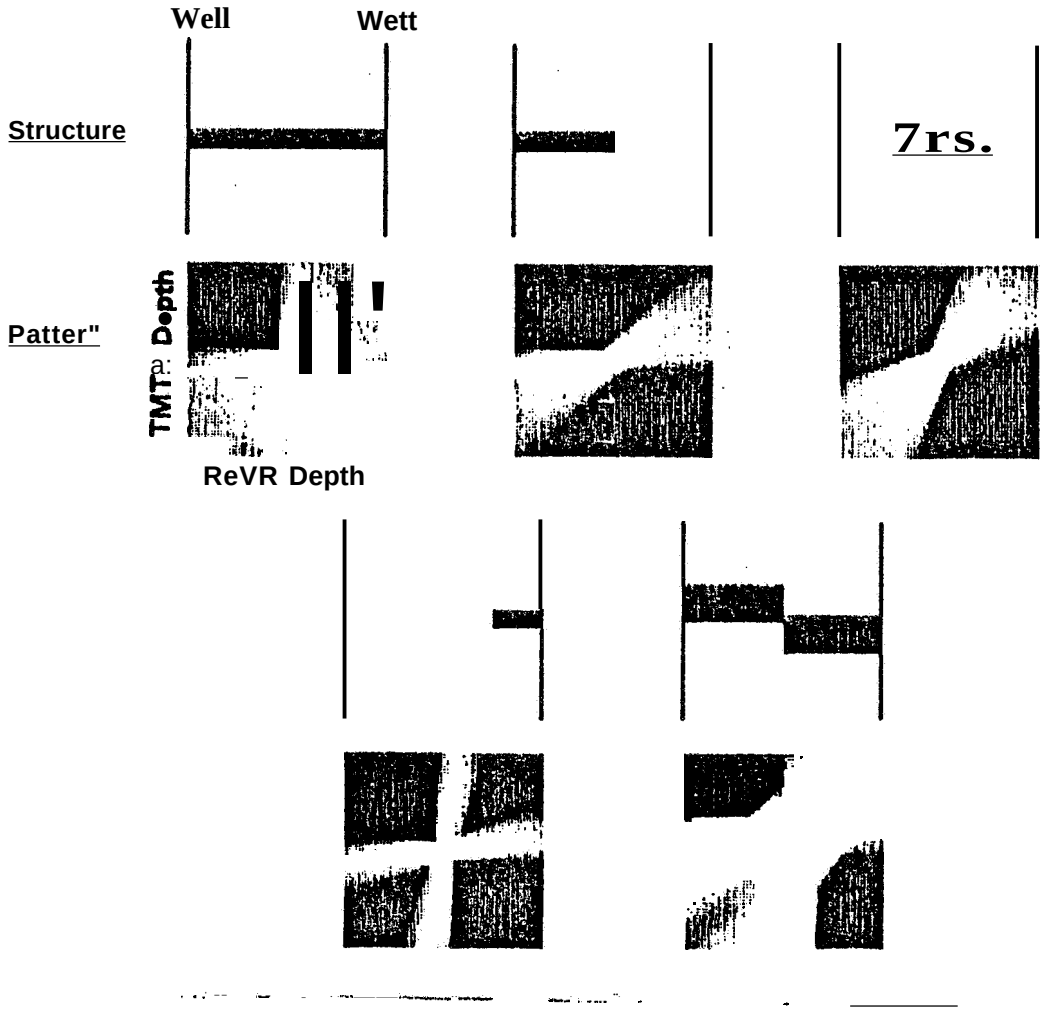


Fig. 3. Velocity log Patterns (Darker Tones Correspond to Higher Velocity)

and (5) a sand faulted between wells, The pattern for each structure is remarkably different. For example, figure 3 shows the velocity change at the base of a continuous bed occurs at identical transmitter depth regardless of the receiver depth of the scan. This pattern is unique. When only incomplete patterns are recognizable, interpretation in terms of structure is non-unique; however, even in these in.stances the infonnation contained in the Schlumberger Sonic Logs may force uniqueness. That is indeed the case for the Coastal Zone. A sand channel has been located in the 6250-6300-ft depth interval that is not penetrated by either wells MWX-l or MWX-2. Further, we have 1earned the base of the sand identified as Red B by the MWX staff is discontinuous between wells, which is contrary to its assumed structure.

Velocity and Attenuation Characteristics of the Coastal Zone. The average velocity and attenuation for the rocks scanned in the Coastal Zone are shown in Figure 4 as a function of receiver depth. The Coastal Zone is bounded above and below by velocity and attenuation discontinuities that may appear on 3-D seismic surveys of the MWX site. A weak correlation between velocity and attenuation appears to exist. Average acoustic veloeity in general increases with depth. The increase may relate to either an overall decrease in the porosity of sandstone strata, an increase in the sand fraction with depth, or a decrease in overpressure or water saturation. Substantially more study of the implications of the velocity and attenuation changes is warranted because each of the possible phenomena may affect production estimates before stimulation.

Attenuation as a function of depth has been calculated and compiled for each scan. Discontinuous changes in attenuation over short depth intervals as

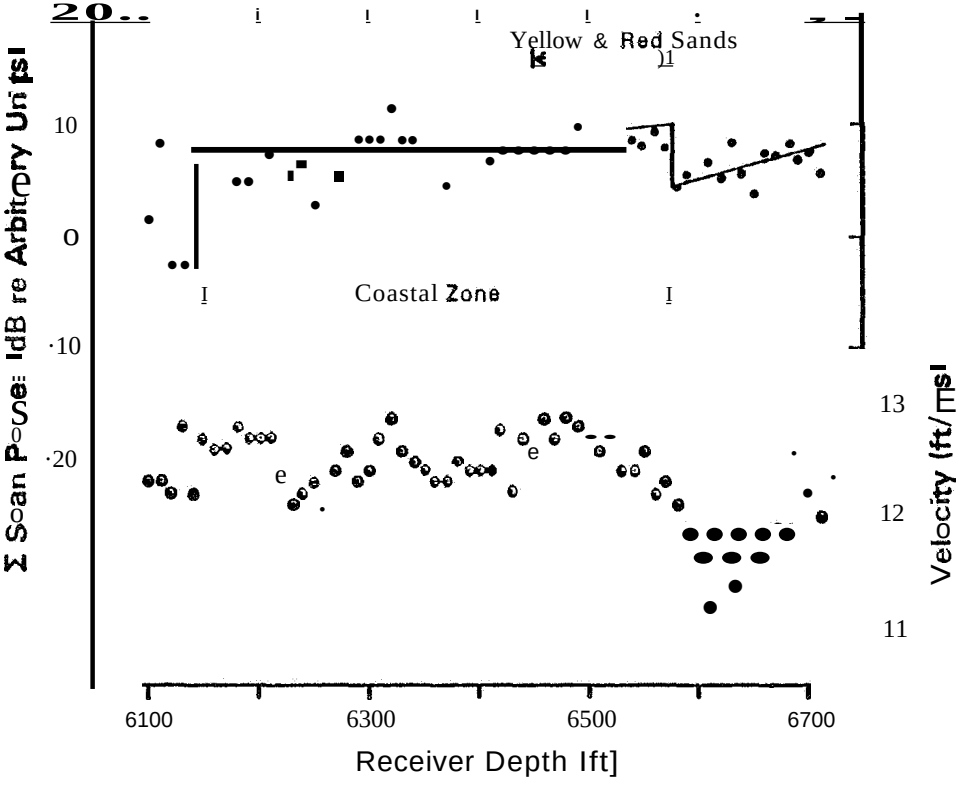


Fig. 4. Relative Attenuation and Average Velocity of Scans in the Coastal Zone

well as substantial asymmetries in attenuation about many receiver positions have been observed. More about this in the section on Sensor Deployment.

Full Waveform Representations of Scan Data. A catalogue containing a condensation of all signals transmitted between wells has been compiled. Reflected, tube, and guided waves as well as head wave first-arrivals can be identified in the catalogued scans. On the basis of Schlumberger Sonic Logs, one would expect that coherent reflectors from lithologic discontinuities should be ubiquitous. They are in fact sparse. Clearly, rock within a few radii of the MWX wells has. been so damaged during drilling that velocity contrasts and thereby acoustic impedances between strata appear much greater than they actually are. The identification of first arriving head waves is important. If head waves are not accounted for in an analysis of crosswell data, twoimage reconstructions will not be possible. In addition, any attempt to map the progress of hydraulicstimulation using microseismlc monitoring techniques will be difficult. Identification of tube and guided waves has even more important implications for crosswell interpretation.

Tube Waves, Waveguiding Strata, and the Coastal Zone. A major fraction of the acoustic energy generated at the transmitter, rather than being directly injected into surrounding rock, is trapped travelling up and down the well away from the transmitter in the fonn of tube or Stonely waves. We have discovered that in the Coastal Zone, tube wave energy in turn leaks out of the transmitter well through strata having appropriate thickness and velocity to form waveguides. The extremely small fraction of the energy trapped in the stratigraphic waveguide that arrives at the adjacent well is reconverted as a tube wave and is detected. Figure 5 shows the travel path through two strata

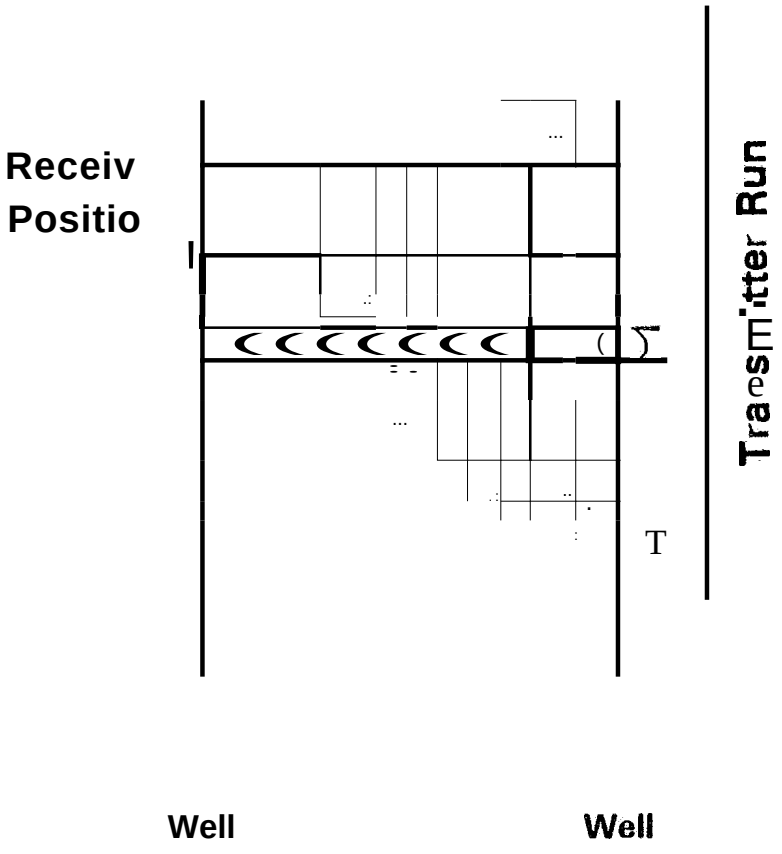


Fig. 5. Propagation Path of Signals Transmitted Between Wells in Waveguiding Structures

from a transmitter position T to a receiver. The thickness of the stratigraphic waveguides dete.cted in the Coastal Zone varies from 3 to 10 ft in thickness. The waveguiding structures we have identified must be continuous between well sand cannot be faulted with a vertical displacement greater than the thickness of the strata.

The presence of clearly visible signals emerging from waveguiding strata implies that crosswell measurements, without additional technological advances in acquisition equipment, are possible at ranges in excess of 500 ftwher.e those structures exist.

Sensor Deployment• Ample information is now catalogued and available for selection of optimum sensor locations within the Coastal Zone for microseismic monitoring of hydraulic stimuTations. Optimum sensor locations are those for which (1) head waves will not be the first arriving signals and (2) the velocity and apparent attenuation structure is as uniform and symmetric about the sensor as possible.

2.0 Two-Dimensional Analysis

The Objective of this project element is to develop, v.alidate, and apply a computational algorithm for the recovery of a two-dimensional velocity image of the Coastal Zone from Multi-Well crosswell acoustic data.

Literature Search - Crosswell Tomography. A 1iterature search was conducted and reviews made for the purpose of (1) determining the state-of-the-art in crosswel1 imaging and (2) reviewing developments in medical and industrial tomography relevant to gas sand imaging. Published literature dealing with crosswell applications is meager - nine articles in all. Half of that

1iterature was pubHshed in the past year. In studying:.the 1iterature, one sees little progress in technical capability or theory; claims are poorly supported by the results presented, conflicts within and between articles are not resolved, and a common basis for evaluating the performance of tomographic algorithms has not evolved and paradigms have not emerged. Most of the literature reports the effect of noise and refracted travel paths on numerical simulations of image reconstruction of simple geologic structures. Image distortion due to the 1imited aperture imposed by constraints on crosswell measurements is acknowledged but subsequently ignored. Little practical experience is evident. Three attempts have been made to reconstruct velocity images using real data, but the attempts have been with extremely limited data sets. It may be safely said that geophysical tomography, particularly cross-well imaging, is struggling to be born, in stark contrast to the accumulated experience and practice in the medical and industrial fields.

The Los Alamos Tomography Code. An extensive ensemble of tomographic software was made available to CAIP through the weapons program at Los Alamos. Included was an algorithm for (1) ART, (2) prediction of acoustic-wave travel time through mechanical structures, and (3) extensive graphics support. CAl? is collaborating with the original developers of the code at Los Alamos in modifying and validating the code for crosswell applications.

The original code has been modified to calculate travel times through simple geologic structures that might be found in the Coastal Zone. An algorithm has been implemented to sort data obtained, using crosswell scans into the parallel beam fonnat required by the original code. The image field has been changed from a ctrcular to a trapezoidal field representative of the boundaries of the survey conducted in the Coastal Zone.

The Tomographic Process. Since the viewing of a geologic structure situated between wells from all angles is precluded (the limited-aperture problem), insufficient data are available with which to recover the exact image of the structure, and so distortions result, In attempting to recover a velocity image:

(1) a starting image (stratigraphy) is assumed;

(2) the travel time for all signals transmitted through that image is predicted;

(3) predicted and measured travel times are compared, and

(4) differences in travel time are used to improve the current image before repeating steps 2, 3, and 4.

The starting image may be an exact replica of the image we seek to reconstruct,or commonly, an image having a constant veloeity throughout the field of view is used.

In evaluating tomographic algorithms, reconstructions for which exact images or constant-velocity images are initially assumed, we find the least and greatest distortions in final calcu1ated images that will occur using the code. In actual practice using measured values, image distortion will probably 1ie between the two extremes because beneficial starting images can be constructed using data derived from wellbore geophysical logs and stratigraphic interpretations. Mitigating this benefit are deleterious effects of measurement error.

Limited-Aperture Reconstructions. Without modification, the Los Alamos code was used to study the effect of 1imited apertures on image reconstructions. Aperture, expressed in terms of crosswell measurements, is the tncluded angle at the receiver of the triangular, scanned area between wells. For the

Coastal Zone measurements, the aperture is an approximately constant value of 100°. For industrial applications, the aperture is often 180°.

The images shown in Figure 6 were calculated fora rectangular object in the center of a field of view having a range of aperture of from 180° to 60°. The reconstructions were made using constant-velocity starting images. With decreasing aperture, the amplitude and orientation of the distortions change. Another set of calculations (not shown in Figure 6)were made in which a rectangular analogue of a sand channel was rotated in the field of view having a 90° aperture. Distortions were least, parallel to the wellbore boundaries. The shape of the channel was·best resolved when the channel was tipped 45° on its side. Highly dipping structural features Iccated between wells will thus be least resolved by crosswell measurements.

Testing - Simple Geologic Structures. Tests of the modified Los Alamos code were made using predicted travel times through the simple geologlc models shown in Figure 7. For each model a reconstruction was derived for both exact and constant-velocity starting images. The reconstruction for constant-velocity images are shown. In our judgment, if an image of the quality Obtained using the constant-velocity starting image could be recovered from the Coastal Zone measurements, this would be of great value to the MWX Project and gas sands technology.

Testing - Sattler's Stratigraphic Cross Section. Figure 8 shows an image reconstructed (bottom) from synthetic travel times derived from a simplHied model of Sattler's interpretation of the Coastal Zone (top). We have separated the Coastal Zone exclusively into sand and "other" stratigraphy and

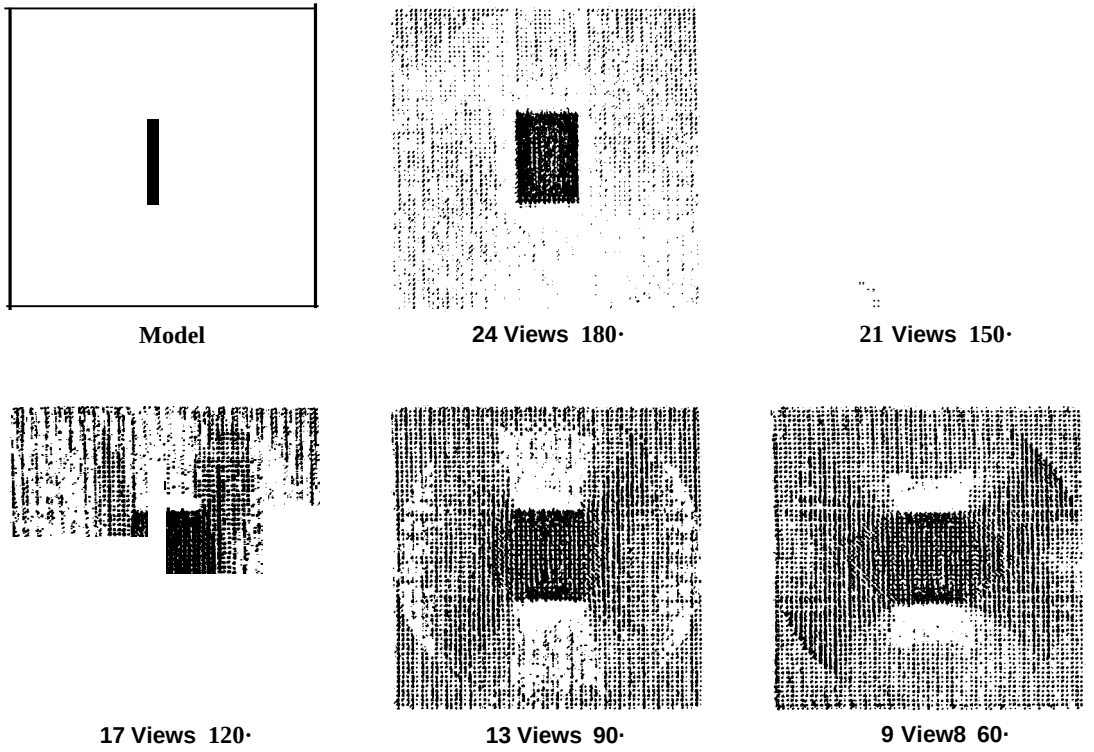


Fig. 6. Effect of Limited-Aperture Viewing on Image Distortion

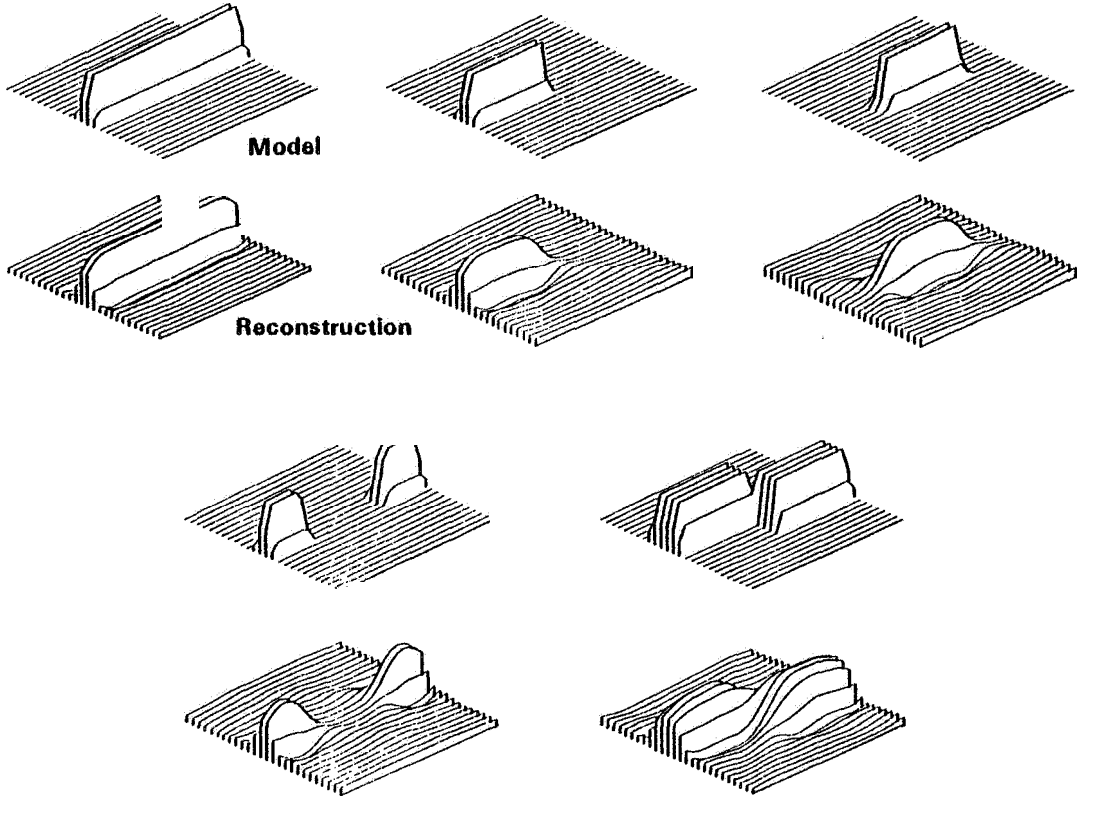


Fig. 7. Reconstructions of Simple Geologic Structures Using Average Velocity Starting Image

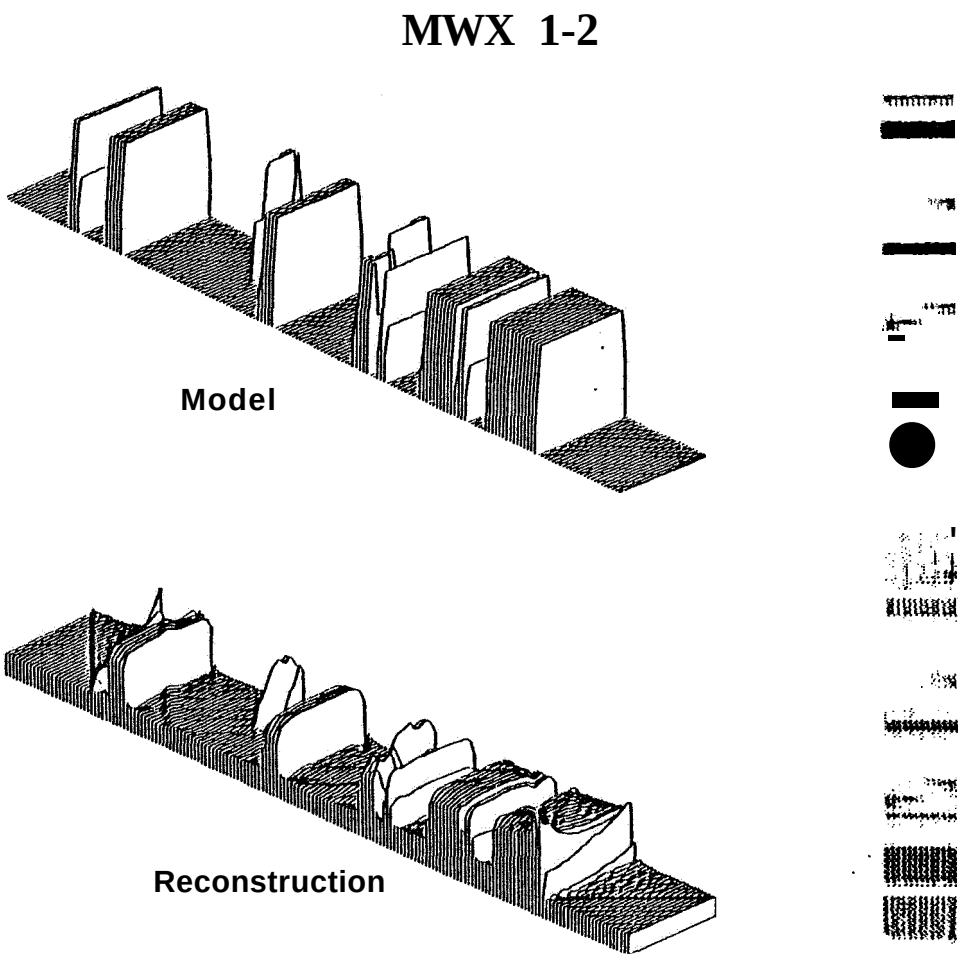


Fig. 8. Reconstructions of a Simpl Hied Version of Sattler's Stratigraphic Cross Section

have assigned a constant velocity to each. The assignment of a constant velocity to the major sands is fully justified based on information contained in the CAVL and the Schlumberger Sonic Log. The "other" stratigraphy (coals, shales, and minor sands) characteristically are thin interbedded layers which are highly variable in velocity. One can thus expect that in recovering the image of the Coastal Zone using real data, the major sands will stand out against a chaotic background of high-velocity contrasts as broad smooth regions of slowly varying velocity. In this case we will have obtained a poor image of the fine structure of the Coastal Zone, but also a much better image of the gas-bearing sands, the latter being just the sought after result.

3.0 FY84 Crosswell Measurements

Previous Crosswell Measurements. The principal objective of the 1982 measurements was lito establish whether crosswell acoustic studies were possible at the MWX sfta." Secondary objectives were: "(i) to collect sufficient crosshole data so that pretreatment conditions could be determined • • ., (ii) to provide quasi-one-dimensional analysis of selected crosshole scans, and (iii) to determine whether two-dimensional analyses --- were warranted ." (Ref., Albright J. N., Los Alamos MWX Crosswell Acoustic Measurements, Technical Memorandum to D. A. Northrop, 2/7/83.) The objectives of the 182 measurement program were fulfilled. The Coastal Zone data taken" during that project form the empirical basis for the developmental work underway in the Western Gas SandsCAIP.

Since 182 the Multi-Well Experiment has increasingly refined knowledge of the Coastal Zone and has identified uncertainties (i.e., the continuity, or lack thereof, of certain sands between wells) that, if resolved, would substantilly impact experimental plans, The '82 data are inadequate to satisfy the current sophistication of Multi-Well Experiment needs. The new crosswell measurements wi11 rectify this situation.

The New Measurements. The principal intent of the new measurements is to examine the Coastal Zone at the highest resolutton: practicable from vantage points that will include MWX-3. In contrast with the firstsurvey, this means reducing the receiver spacing from 10 to 3 ft, reversing the MWX 1-2 survey (the substitution of a transmitter for receiver and vice versa in a second complete survey), and taking measurements between MWX 1-3 and MWX 2-3. All of the major sands in the zone will be stUdied. Improvements in overall data quality can be expected due to certain subassembly design and component

changes made in the borehole tools. In addition, better survey designs are now possible as a result of Los Alamos work completed in the first quarter of FY84.

Schedule. Wellbore Cood;tions. and Operations Support. Two calendar weeks of scheduled access to the MWX wells are necessary to complete the new measurements. In-well operations are expected to be completed in four working days. Three days each should be allowed for rigging and contingencies. Each well should be water-filled to the surface. Borehole fluids should be free of entrained gas. Access to saOO-ft depth is necessary to survey the deepest major sand in the coastal zone, the Red Sand. Los Alamos will field all necessary equipment for its operations with the exception of the wellhead tower (or similar provision) for the rigging of wireline sheave and lubricators. A field engineer representing the Multi-Well Experiment and having knowledge of conditions in the MWX wells should be present throughout the entire Los Alamos operations.

los Alamos Crosswell Imaging Project

Fiscal Year 1984

	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
1.0 One·Dlmenllonal AnaIYII.												
1.1 Coastal Zone 6200-6800												
1.2 Jun 84 Measuremellts												
2.0 Two-Dlmellllonal Analysis 8												
2.1 literature Review and Task Guidllilne												
2.2 Code Modifications and MWX Trials												
2.3 Coastal Zone ART 1821												
3.0 MWX Cronwell Mea.uremeilt.												
3.1 Preparations and Survey Design												
3.2 Field Measurements												

* Algebraic Reconslruc!ion Tomographv CARll

Appendix B

Task Statements

1.0 One-Oimen.sional Analysis

1.1 Coastal Zone 6200-6800. Velocity: Measure average and interval P-wave velocity for the 62 scans taken in the 1982 survey of the Coastal Zone. Prepare a crosswell acoustic velocity log of the zone. Identify and characterize the velocity signature of the major sands. Full wave: Plot the waveform of stacked signals within each scan corrected for (direct ray path) normal moveout, geometric spreading, apparent attenuation, and the radiation patterns of source and receiver. Identify coherent reflectors and locate their position if possible. Examine plots for evidence of waveguiding structures and locate those structures. Calculate and plot the relative attenuation for each tran.smittedsignal. Analyze and interpret the above results in the context of tight sands properties and structures exhibited in the Coastal Zone.

1.2 June'84 M.easurements. Process the new data acquired at Rifle as described in Task 1.1

2.0 Two-Ojmensiona1 Measurements

2.1 Literature Review and Task Guideline (Development). Review relevant medical/industrial and all geophysical 1iterature to assess current state-of-the-art in 1imited-view tomography. Identify potential sources of applicable computer software. Develop overall guidelines for Task 2.0 in the context of the requirements of imaging tight sands and of the successes (and failures) in the historical development of tomography.

2.2 Code Modifications and MWX Trails. Modify HART (Hanson's Algebraic Reconstruction Tomography) for optimum velocity-image reconstruction of

the Coastal Zone data. Make pravision *for* flexibility in survey design, convenience of data-input, and grey-tone and relief presentations of data.

2.3 Coastal Zone ARna2l. Load into computer memory acoustic-signal time-af-flights, wellbore trajectories, and the scan coordinates of transmitter and receiver. Using the code developed and tested in Task 2.2, reconstruct the velocity image *for* the Coastal Zone within the resolution provided by the 1982 survey. Quantify sensitive parameters in the image reconstruction. Evaluate and interpret image reconstructions.

3.0 MWX Crosswell Measurements.

3.1 Field Preparations and Survey Design. Prepare the field operations plan, service the borehole tools, and reconfigure the data recording system *for* crosswell surveying. Prepare the measurement design for closely spaced surveys of the Coastal Zone from each well pair. Load wellbore gyrosurveys into computer memory and calculate optimum measurement designs based on transmitter/receiver acoustic radiation patterns, geometric spreading, and apparent attenuation.

3.2 MWX Field Measurement. Survey the Coastal Zone sediments penetrated by the MWX wells at Rifle.

Project Personnel

James N. Albright. Jim is co-investigator on the Crosswell Acoustic Imaging Project of the Western Gas Sands Subprogram. He received his PhD degree in Geophysical Sciences from the University of Chicago in 1969. Subsequently he was Assistant Professor of Geophysics at Syracuse University. Since 1974, he has been employed at Los Alamos National Laboratory in various capacities. Jim formed the Geophysics Group at Los Alamos in 1980 and served as its first Group Leader. More recently, he has been staff member and Deputy .Group Leader for Geological Engineering. His research has concentrated on the design and analysis of borehole seismic/acoustic measurements of rock and reservoir properties in support of Hot Dry Rock, Hydrothermal, National Security, and Multi-Well Programs. Recent pres·entations and pUb1 ications incl ude:

- Albright, J. N. and Terry, D. A. (1984), "Seismic Measurements in Deep Boreholes," presented at the International Symposium on Observations of the Continental Crust through Drilling, May 21-25, Tarrytown, N.Y.
- Batra, R., Albright, J. N., and Bradley, C. (1984), "Downhole Microseismic Monitoring of an Add Treatment in the Beowawe Geothermal Field," to be published in.the Proceedings of the Geothermal Research Council, October, Reno, NV.
- Pearson, C. F., Feh1er, M. C., and Albright, J. N. (1983), "Change in Compressional and Shear Wave Velocities and Dynamic Modu1ii During Operation of a Hot Dry Rock Geothermal System," Jour. Geophy. Res., *v*, 88, 3468-3475.
- Albright, J. N. and Pearson, C. F. (1982), "Acoustic Emissions as a Tool for Dry Rock Site,' SPE Jour., 525-530.

Darrell A. Terry. Darrell received academic training, including an MS degree in 1976, at the University of Washington. He has been employed at the Los Alamos National Laboratory since late 1983 as a Visiting Staff Member and the co-investigator on the Crosswell Acoustic Imaging Project. His professional background includes acoustical modelling in the aerospace industry, marine seismicsoftware development for Western Geophysical Co., and most recently managing product development in North America for commercial borehole seismic software at Schlumberger Well Services.

Pertinent pUblications include:

- Fyle, t, M. and Terry, O. A. (1977), A Galerkin Finite Element Model of Acoustic Propagation in Ducts With Shear Flow. Report to the BoeingConmercial Airplane Company.
- Albright, J. N. and Terry, D.. A. (1984), "Seismic Measurements in Deep Boreholes," paper presented at the International Symposium on Observations of the Continental Crust through Drilling, May 21-25, Tarrytown, N.Y.

Appendix 0

Project Technical Memoranda

Albright, J. N., IlProject Monthly Report,1I November … June, FY84.

Albright, J.N. and Bradley, C., IlCrosswell Acoustic Velocity Log for the Coastal Zone,1I February 16, 1984.

Albright, J. N. and Bradley, C., "Catalogue of Full Wave Representation of Acoustic Signals Transmitted Between Wells in the Coastal Zone,ıı April 16, 1984.

Albright, J. N. and Bradley, C., IICatalogue of Acoustic Attenuation Scans in the Coastal Zone,Ⅱ June, 1984.

Bradley, C., "Inf'luence of Refracted (headwave) Arrivals on Crosswell Acoustic Surveys,Ⅱ March 13, 1984.

Terry, D., IICrosswell Acous'cic Tomography - Review of the State-of-the-Art for Gas Sands Applications,1I December 17, 1983.

Murdock, M., "Algebraic Reconstruction Tomography - Programs Developed for the HP-85 Persona1 Computer," January 16, 1984.

TITLE:	MULTI-WELL EXPERIMENT CORE PROGRAM
ORGANIZATION:	SANDIA NATIONAL LABORATORIES/ CER CORPORATION
PRINCIPAL INVESTIGATOR:	ALLAN R. SATTLER
PERIOD OF PERFORMANCE:	CONTINUING
CONTRACT FUNDING:	AN APPROXIMATE 2 FTE RATE

OBJECTIVE:

PROVIDE PHYSICAL PROPERTY DATA FOR

DESCRIPTION OF RESERVOIR

INPUTS FOR WELL TESTING AND STIMULATION

GOALS:

RESERVOIR ENGINEERING PARAMETER DATA

STRESS AND ROCK MECHANICS PROPERTIES

DEtAILED GEOLOGICAL ANALYSES

HVDRAULIC FRACTURE DESIGN DATA

INPUtS TO LOG-CORE CORRELATIONS

MWX CORE PROGRAM

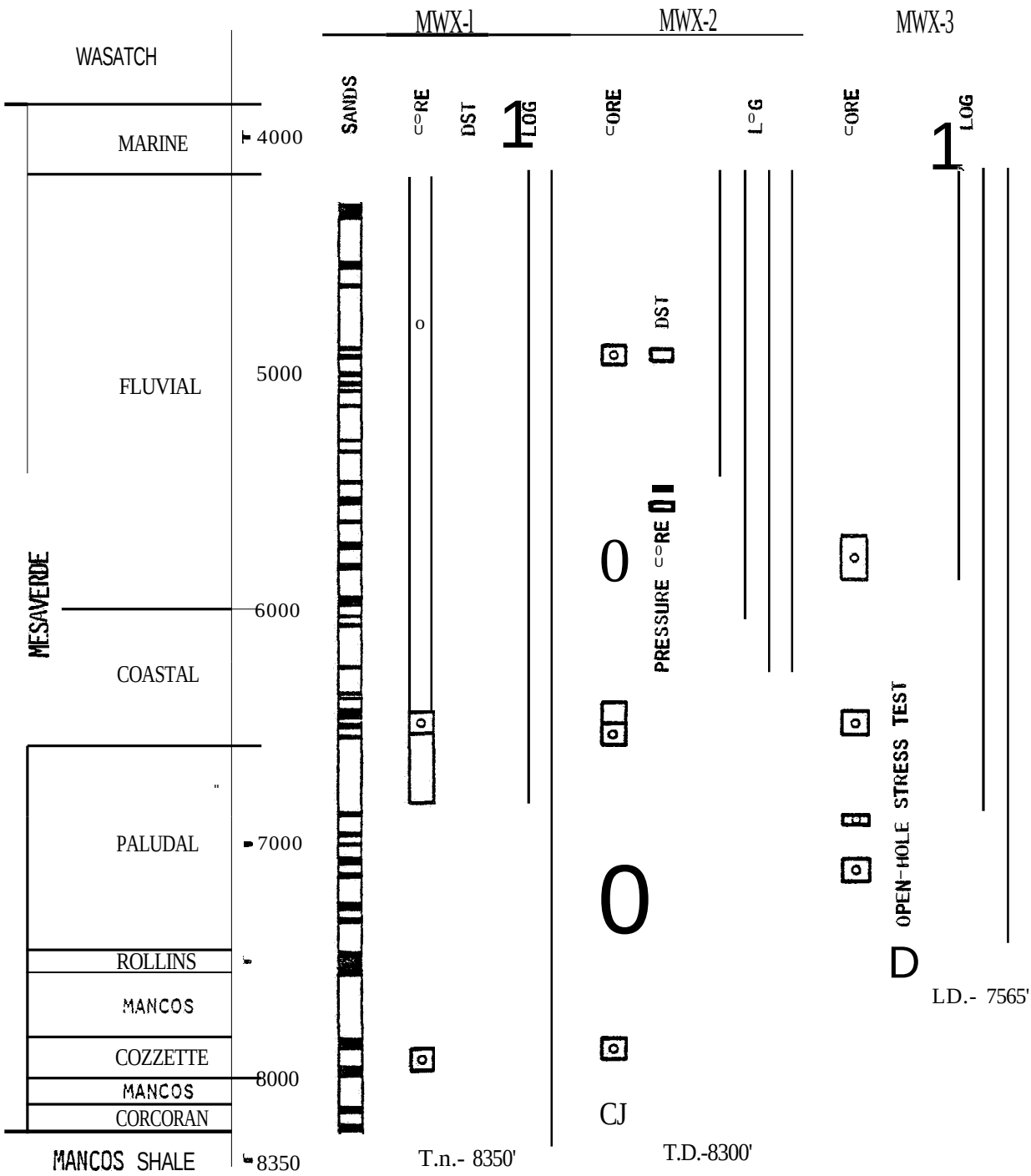
FEATURES

- INVASION STUDY
- SPECIAL EQUIPMENT AND PROCEDURES
- PRESSURE CORE
- FIELD PROCESSING PACILITV
- CORE LIBRARY
- OVER 20 PARTICIPANTS

ANALYSES

GROUTINE 8CREENING

- RESTORED STATE PARAMETERS
- MECHANICAL/ELECTRICAL PROPERTIES .
- MINERALOGYIPETROLOGY
- GEOCHEMISTRY
- . ORGANICUATUAATION
- NATURAL FRACTURES
- FRACTURE CONDUCTIVITV
- DEPOSITIONAL ENVIRONUENT81 SEDIMENTOLOGV
- CORI-LOO CORRELATIONS


MWX-1
MWX-2
MWX-3
WASATCH
MARINE
FLUVIAL
MESAVERDE
COASTAL
PALUDAL
ROLLINS
MANCOS
COZZETTE
MANCOS
CORCORAN
MANCOS SHALE
4000
5000
6000
7000
8000
8350
SANDS
CORE
DST
LOG
CORE
DST
PRESSURE CORE
LOG
CORE
OPEN-HOLE STRESS TEST
LOG
CJ
T.n.- 8350'
T.D.-8300'
LD.- 7565'

MWX CORE ANALYSIS

CORE TAKEN

MWX-l	2700	FT	-	490	ORIENTED
MWX-2	900	FT	-	390	ORIENTED
MWX-3	470	FT	-	ALL	ORIENTED

CORE PROCESSED IN FIELD

WIPING) MARKING) PHOTO

CORE GAMMA

LITHOLOGIC DESCRIPTION

SELECTION OF CORE FOR FURTHER ANALYSIS

PLUGGING) SEALING

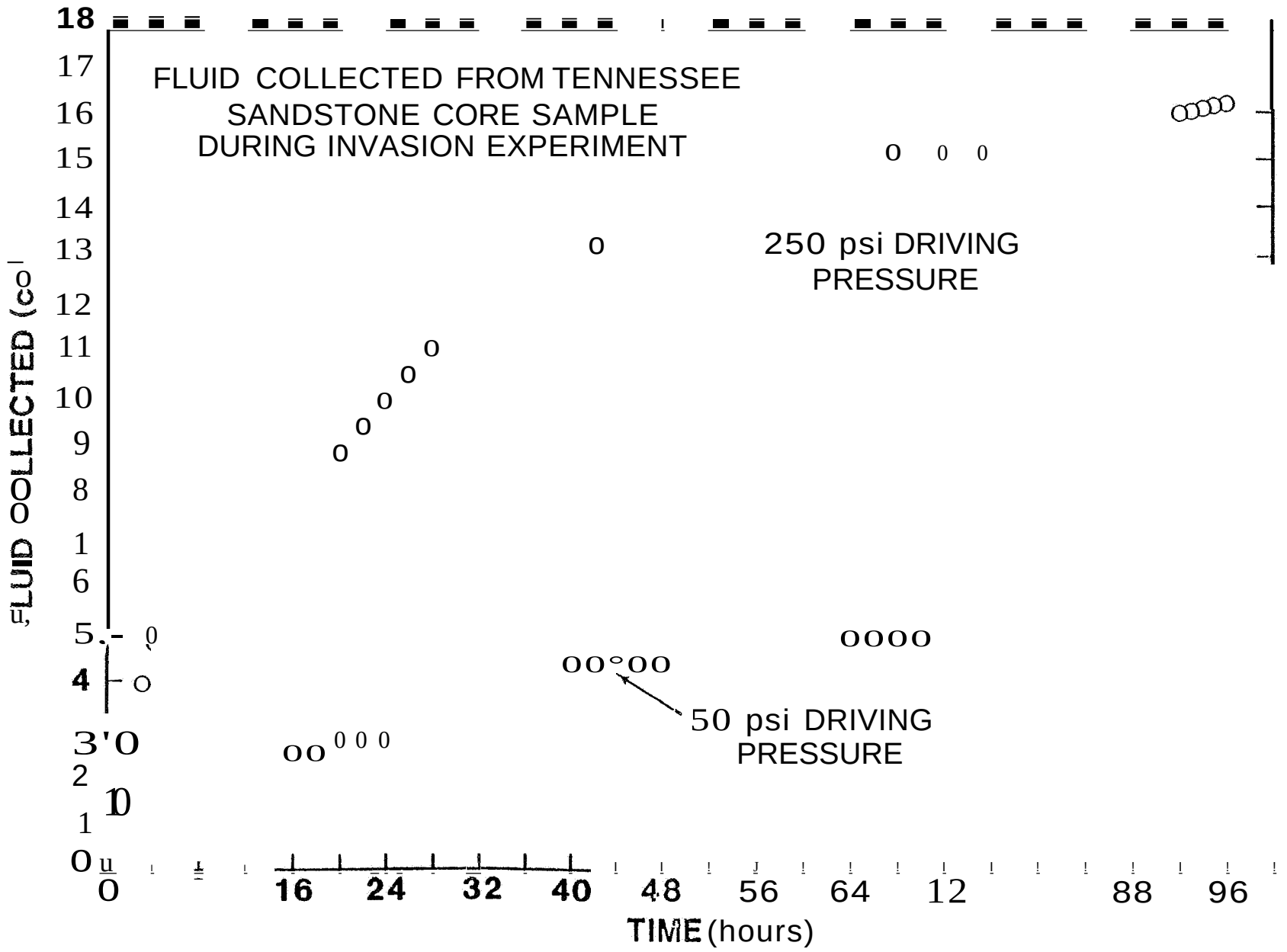
PACKAGING) SHIPPING

CORE LIBRARY WITH COMPUTERIZED INVENTORY

LIST OF PARTICIPANTS

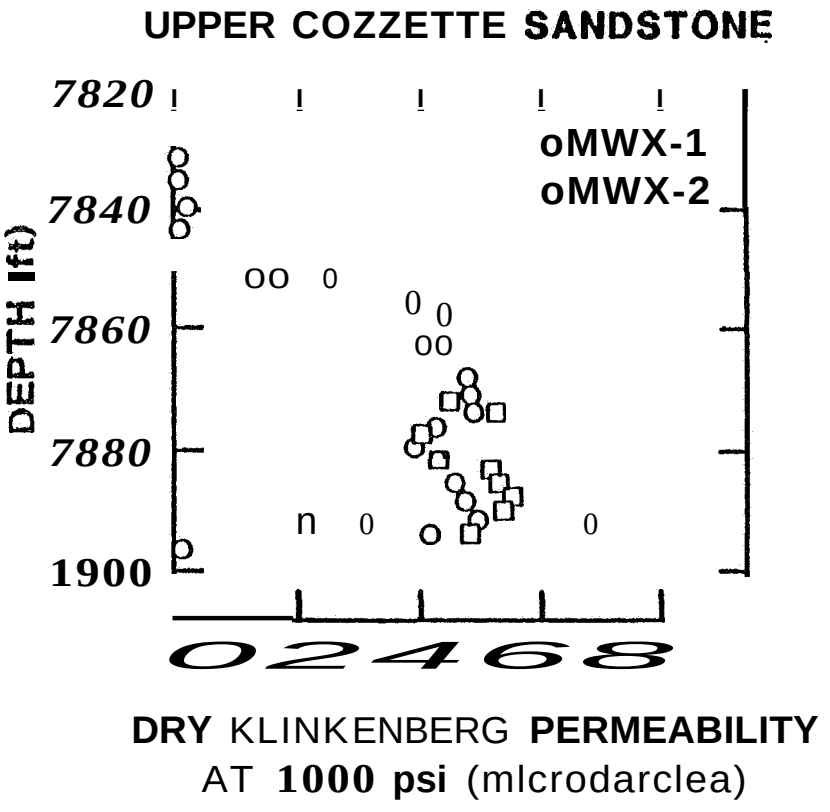
Sponsored by MWX	Sponsored by DOE/METC/WGSP	No Cost to Project
Core Labs*	USGS	Amoco
IGT*	LLNL	Mobil
RE/SPEC*	NIPER	Dowell
Bendix*	PRRe (New Mexico Tech)	Colorado G.S.
PRRC (New Mexico Tech)	IGT	TRW
Texas A&M (rock properties)	Michigan Tech	Texas A&M (sedimentology)
UNM	Terra Tek	SMU
Smith **		Stanford
Western **		Schlumberger
		USGS (Water Analysis)
		Core Labs (Special Routines)

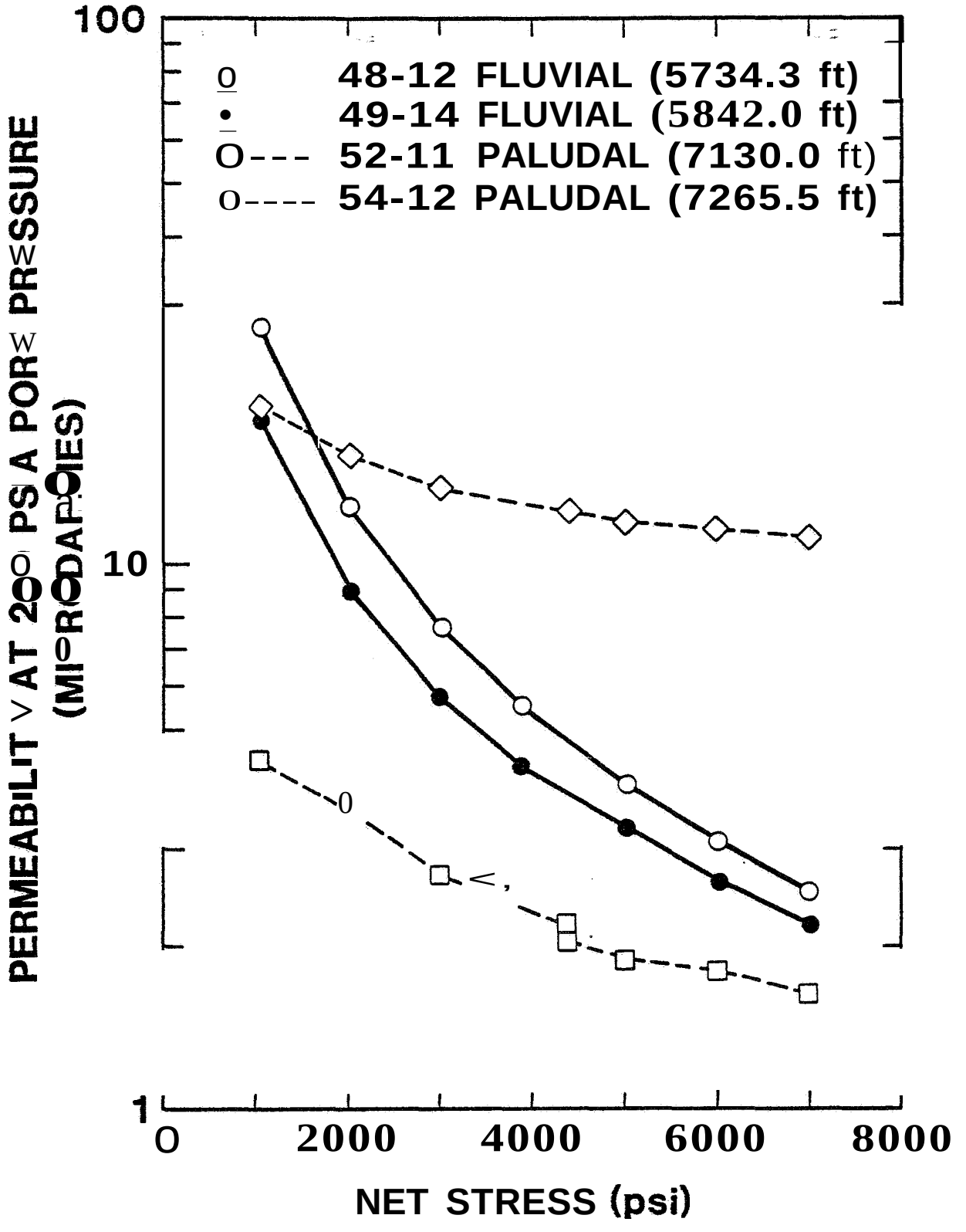
* Major Contractor Laboratories for Project
** Part of Stimulation Contracts

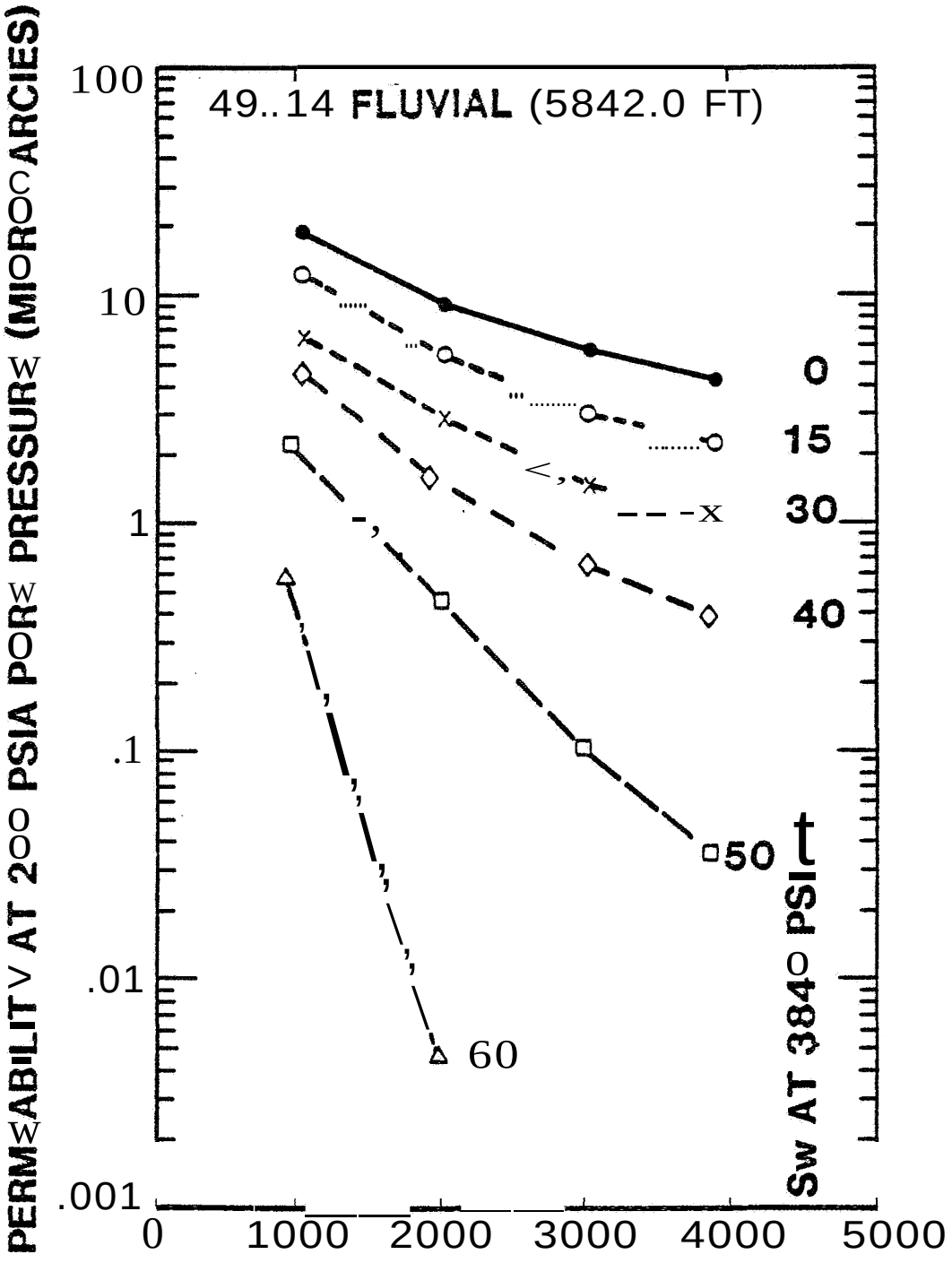

FLUID COLLECTED FROM TENNESSEE
SANDSTONE CORE SAMPLE
DURING INVASION EXPERIMENT
250 psi DRIVING
PRESSURE
50 psi DRIVING
PRESSURE
FLUID COLLECTED (cc)
TIME (hours)
0
16
24
32
40
48
56
64
12
88
96

- OVER 1500 PLUGS ANALYZED FOR ROUTINE ANALYSIS

- SPECIAL CORe ANALYSIS AT 1-3 FT ACROSS SANDS AND INTO BOUNDING FORMATIONS




48-12 FLUVIAL (5734.3 ft)
49-14 FLUVIAL (5842.0 ft)
52-11 PALUDAL (7130.0 ft)
54-12 PALUDAL (7265.5 ft)
PERMEABILITY AT 200 PSI A POR PRESSURE
(MICRODARCIES)
100
10
1
0
2000
4000
6000
8000
NET STRESS (psi)


49..14 FLUVIAL (5842.0 FT)
PERMEABILITY AT 200 PSIA PORE PRESSURE (MICROCARCIES)
100
10
1
.1
.01
.001
0
1000
2000
3000
4000
5000
NET STRESS (PSI)
0
15
30
40
50
60
Sw AT 3840 PSI

IGT GRAPH

CAPILLARY PRESSURE, SAMPLE
DEPTH 7883.4 tt., MWX-1

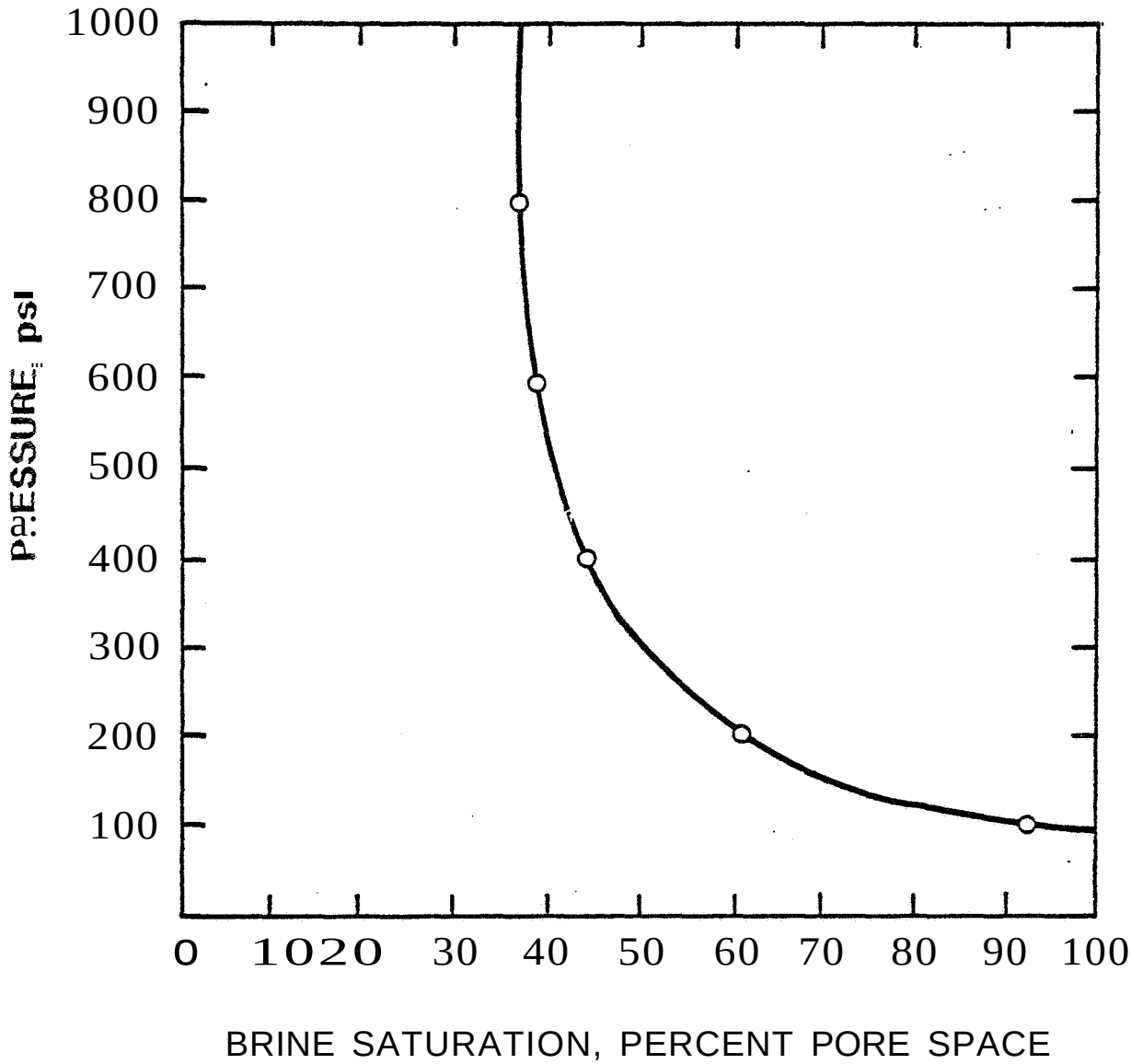


Table I. Permeability Damage Studies (Smith Energy Services)

Depth	Initial Permeability	Treatment	Final Permeability	Percentage of Damage or Improvement
7134.5'-7135.3'	0.071 md	A	0.015 md	-78.9%
7134.5'-7135.3'	0.070 md'	B	0.026 md	-62.8%
7134.5'-7135.3'	0.050 md	C	0.023 md	-54.0%
7134.5'-7135.3'	0.053 md	D	0.054 md	+ 1.9%
7138.75'-7139.6'	0.078 md	B	0.450 md	...41.9%
7138.75'-7139.6'	0.047 md·	C	0.018 md	-61.7%
7138.75'-7139.6'	0.060 md	D	0.059 md	- 1.7%
7081.5'-7082.4'	0.090 md	D	0.093 md	+ 3.4%

CONDITIONS

Temperature .. 210°F
Confining Pressure (around the core plug) - 500 psi

The systems tested were :

A. 50# broken gel

B. 30# broken gel

C. 30# broken gel containing 1 gallon FRS-l (fluid recovery surfactant) per 1000 gallons broken gel.

D. A prepad system called LPM-l (low pH methanol) which consists of 100% methanol containing 7 gallons LPA-91 low pH additive) per 1000 gallons methanol. This prepad system was followed by the 30# broken gel frac fluid containing 1 gallon FRS-l/I000 gallons broken gel.

Contents of 30# and 50il Gels

2% KCl
30# or 50# WGA-2 (gelling material)
0.25 gallons BCS-2 (bactericide)/1000 gallons H20
1 gallon CSP-3 (clay stabilizer)/1000 gallons H20
4# WCB-l (chemical breaker)/1000 gallons H20
BW...4 (buffer) amount needed to attain pH 7.0

PERCENT DAMAGE TO GAS PERMEABILITY OF MWX CORE WITH INCREASING TIME OF EXPOSURE TO FRACTURING FLUIDS (40LB HPG) AT 100°C

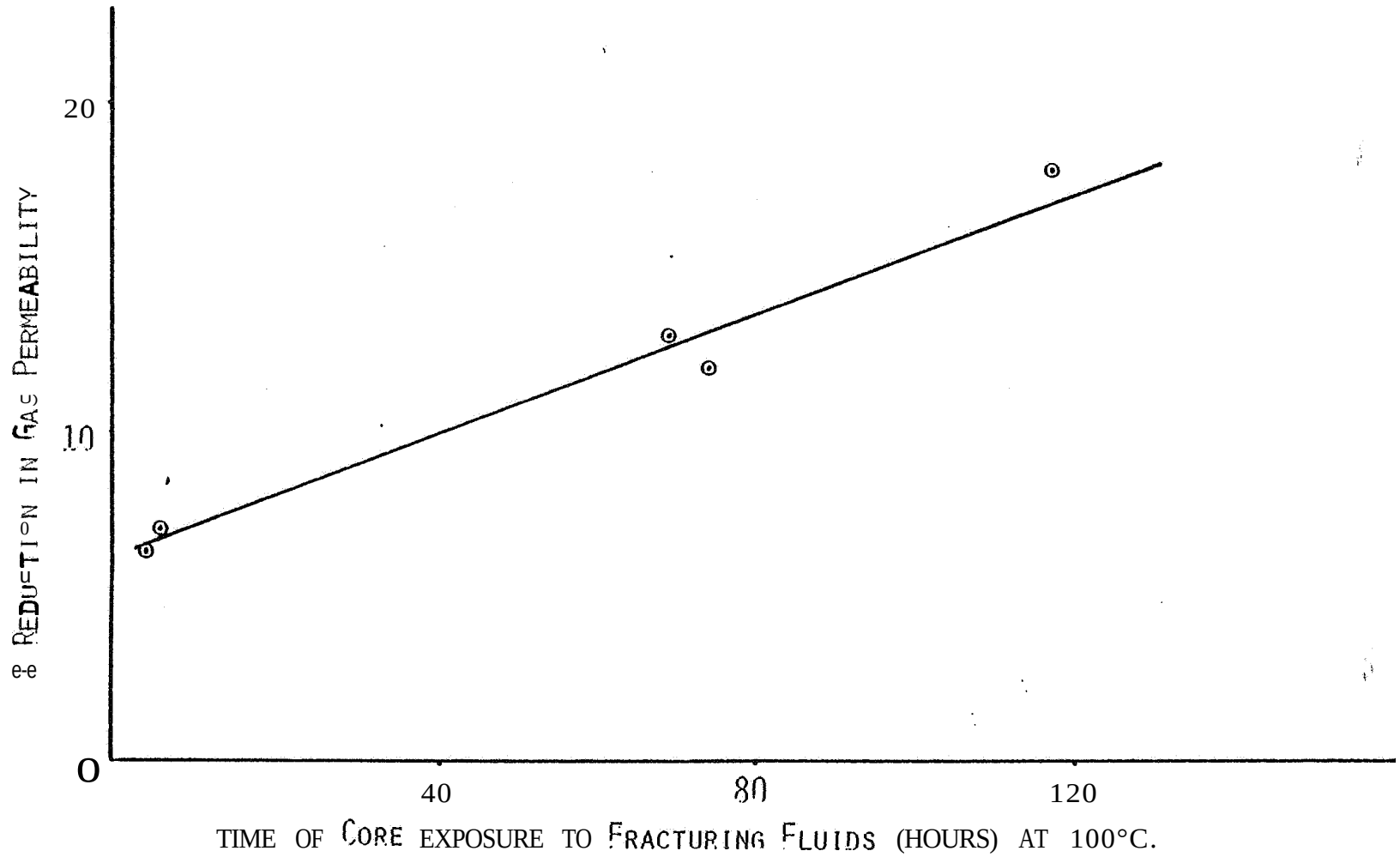


TABLE I. CORRELATION OF ROCK PROPERTY DATA WITH CORE GAMMA AND SONIC LOGS IN BLANKET AND LENTICULAR FORMATIONS

Lithology	Depth (ft)		Gamma Ray Number (arbitrary)	Young's Modulus (GPa)	Inverse Velocity uS/ft
			Blanket Morphology		
Sand	7956.1	(1)	3.5	35	66
Sand	7882.6	(2)	4.5	40	63
Sand	7349.6	(2)	3.0	39	69
Shale	8100.5	(2)	12.5	20	83
Shale	7821.5	(2)	13.0	19	83
			Lenticular Morphology		
Sand	6520.5	(2)	4.0	28	72
Sand	6117.7	(1)	7.0	28	66
Sand	6151.8	(1)	5.5	28	72
Sand	6140.4	(2)	4.0	32	69
Sltst/Mdst	6564.6	(1)	7.5	40	61
Sltst/Mdst	6561.7	(2)	16.0	15	82
Sltst/Mdst	6443.9	(2)	11.0	17	83
Sltst/Mdst	6462.5	(2)	4.0	36	67
Sltst/Hdst	6428.9	(1)	12.0	16	83
Sltst/Hdst	6422.2	(1)	5.5	40	65
Sltst/Mdst	6418.4	(2)	4.5	36	65

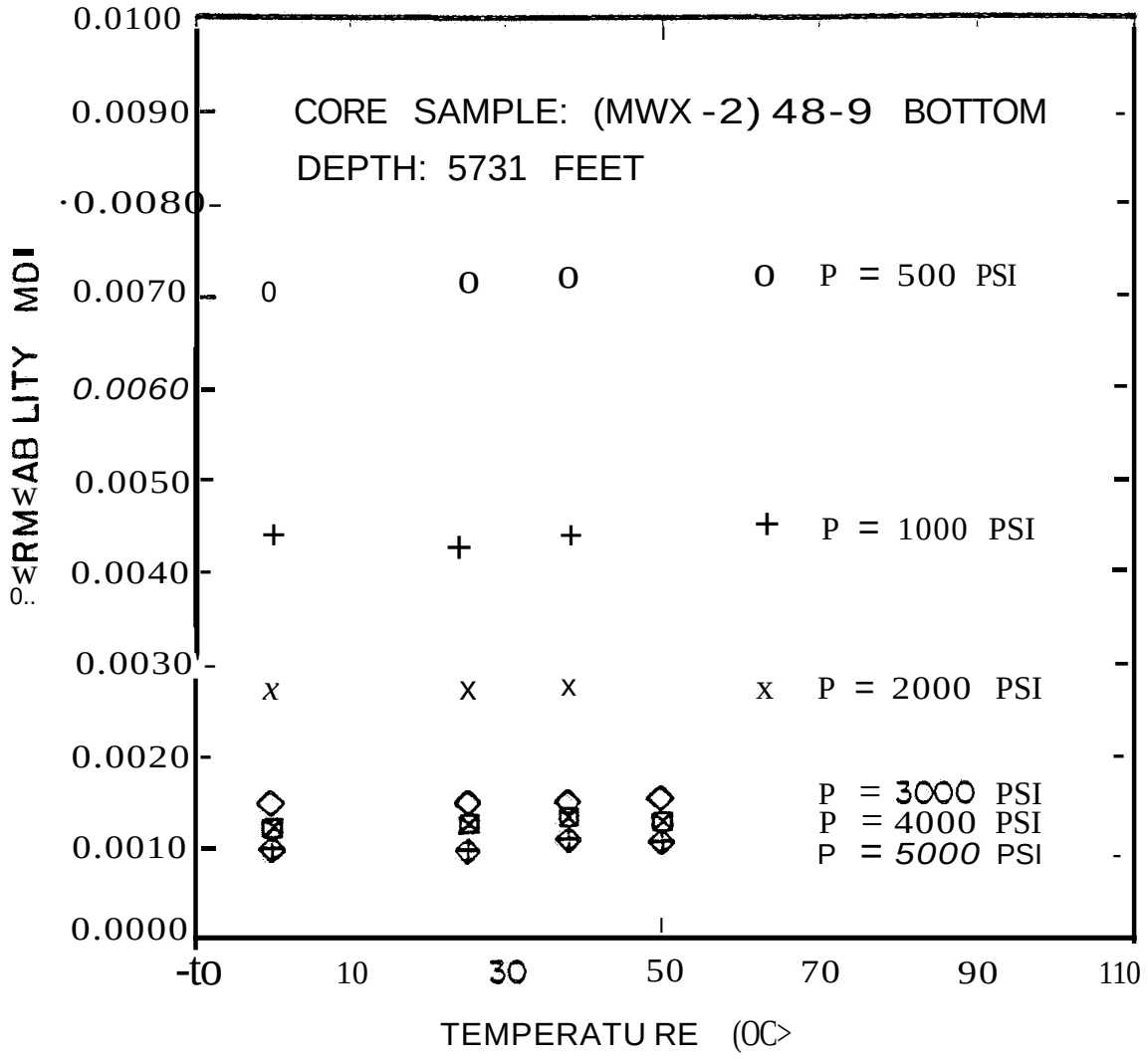


FIG. 3.5. Permeability vs. temperature at various pressure.'

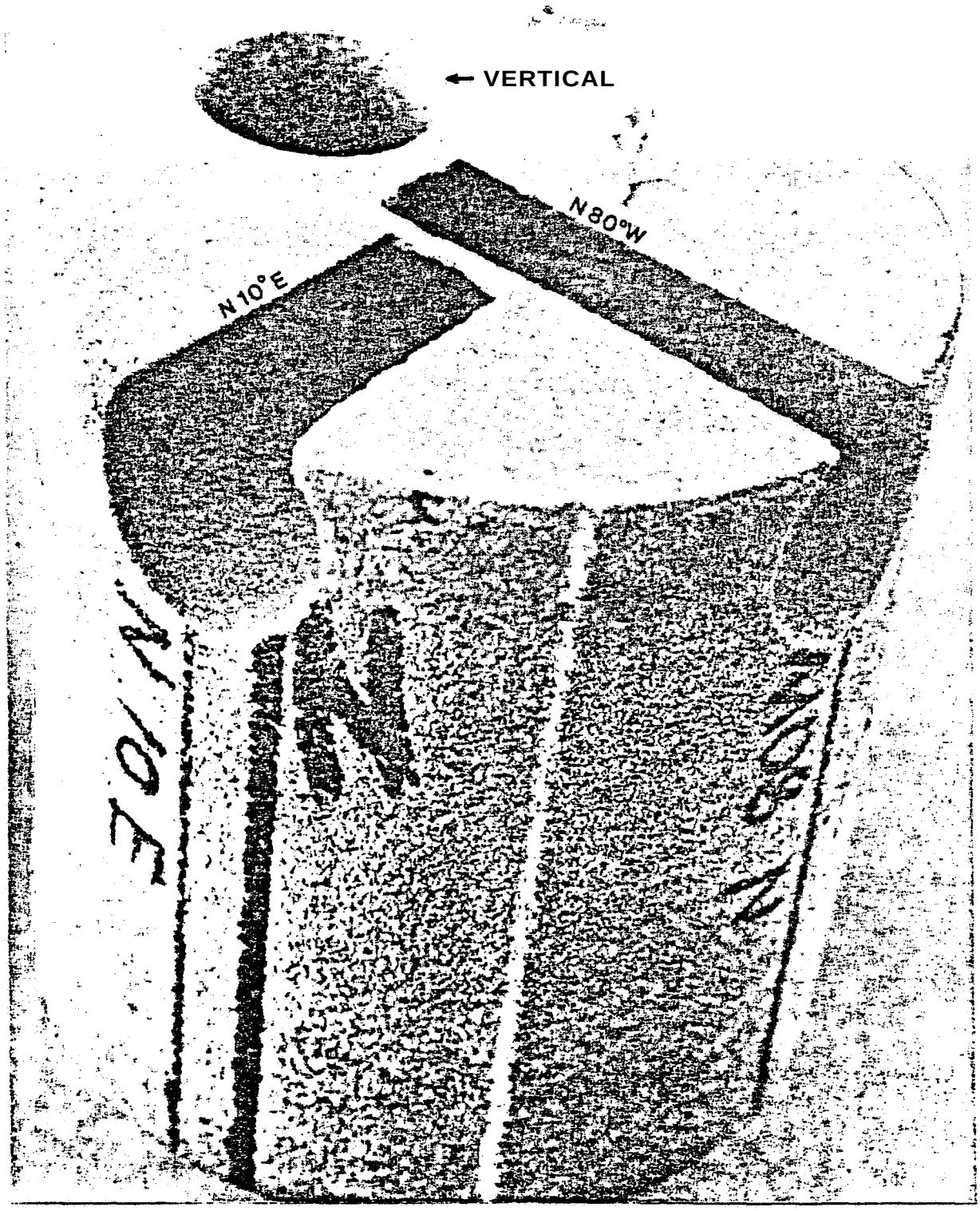


Figure 12. DIRECTIONAL PLUGS CUT FROM A SAMPLE OF MWX SANDSTONE CORE.

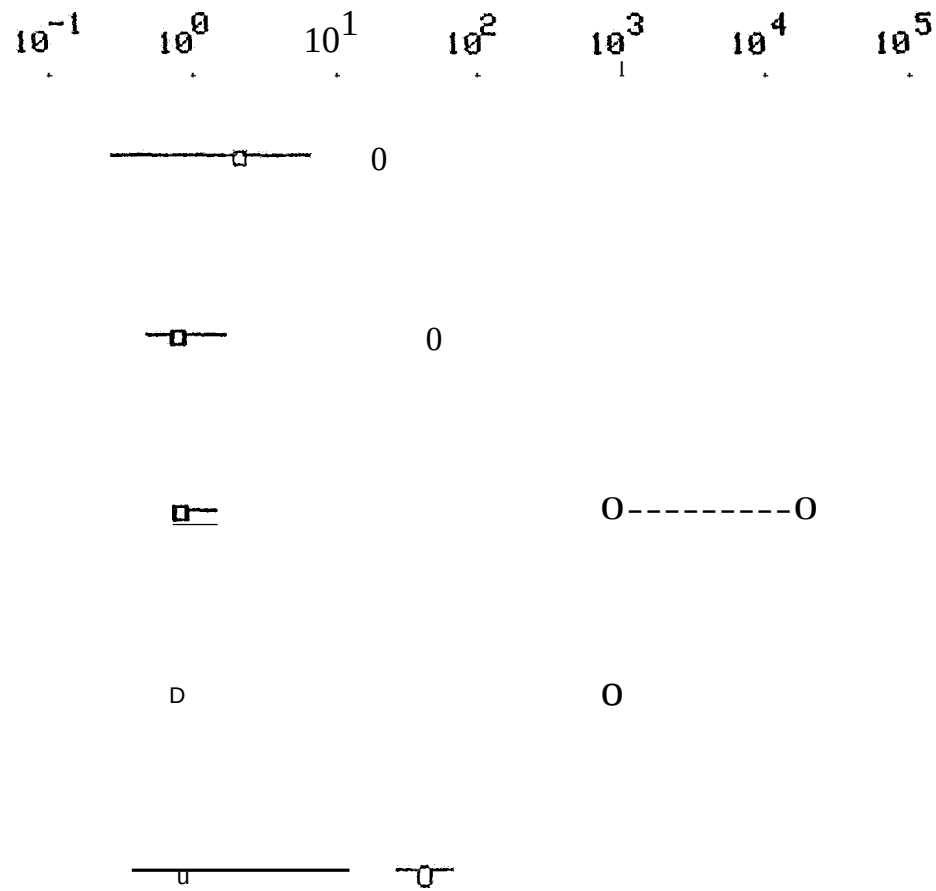
Table 4. MWX DIRECTIONAL PERMEABILITY

Core ID	Dry Permeability to Gas (K_m) Microdarcy		% Greater than	
	N 80° W*	N 10° E	N 80° W Perms	Vertical
MWX-3, 61-13 5737 ft, Fluvial	1.22µd	2.16µd	77%	1.88IJd
MWX-3, 63-12 5830 ft, Fluvial	2.51µd	3.7511d	49%	4.93µd
MWX-3, 64-13 6446 ft, Coastal	1.77lJd	1.8811d	6%	1.16µd
MWX-3, 65-11 6514 ft, Coastal	0.S911d	1.201Jd	35%	0.7411d
MWX-3, 67-10 7090 ft, Paludal	1.4011d	1.95µd	39%	0.56µd
MWX-3, 67-32 7131 ft, Paludal	9.2 µd	11.3 IJd	23%	7.0 IJd

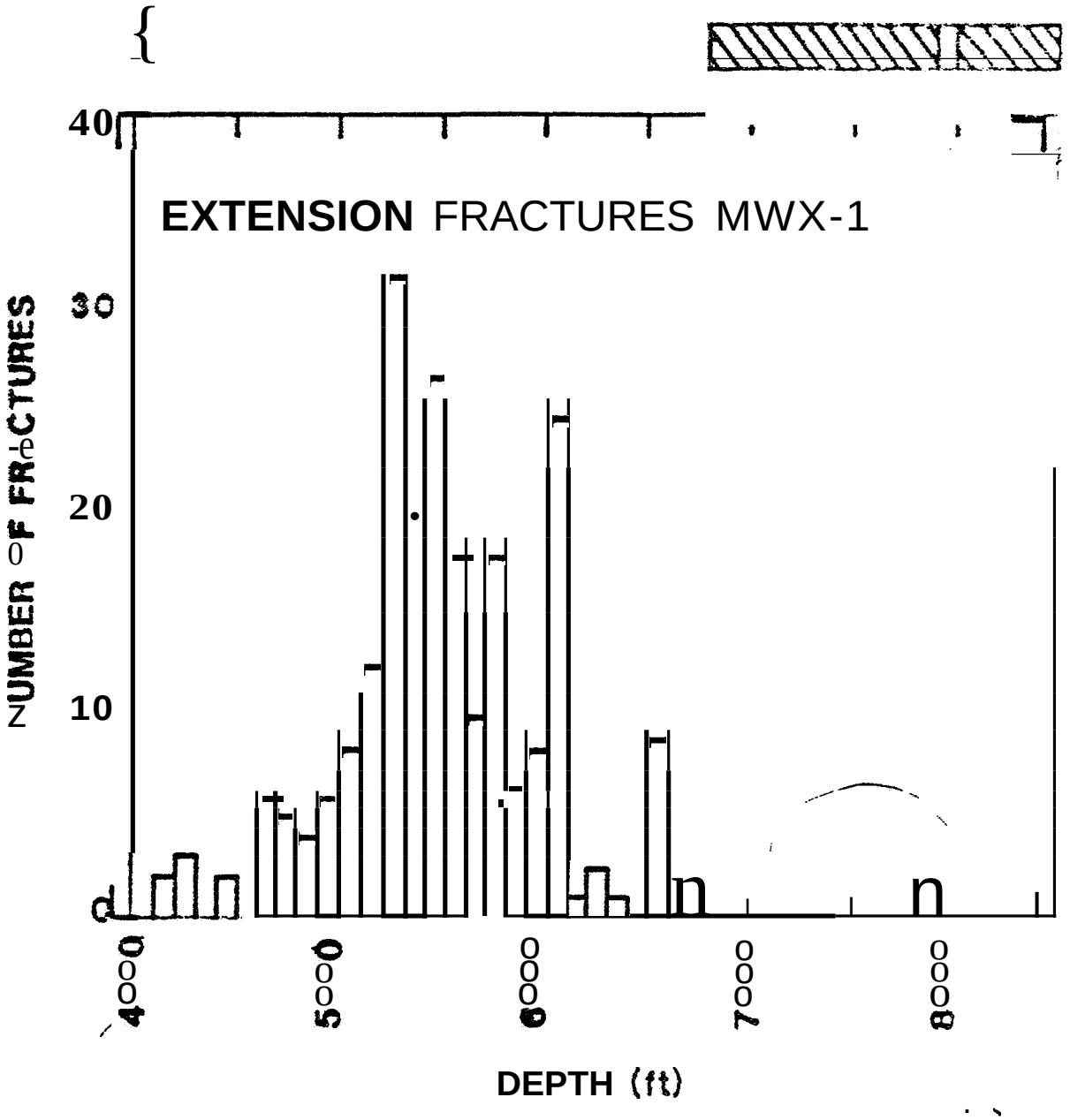
*N SOD W value is from the second CORAL run.

Permeabilities were measured attbe following values of net confining stress: Fluvial cores = 3800 psi; Coastal cores = 4000 psi; Paludal cores = 4200 psi.

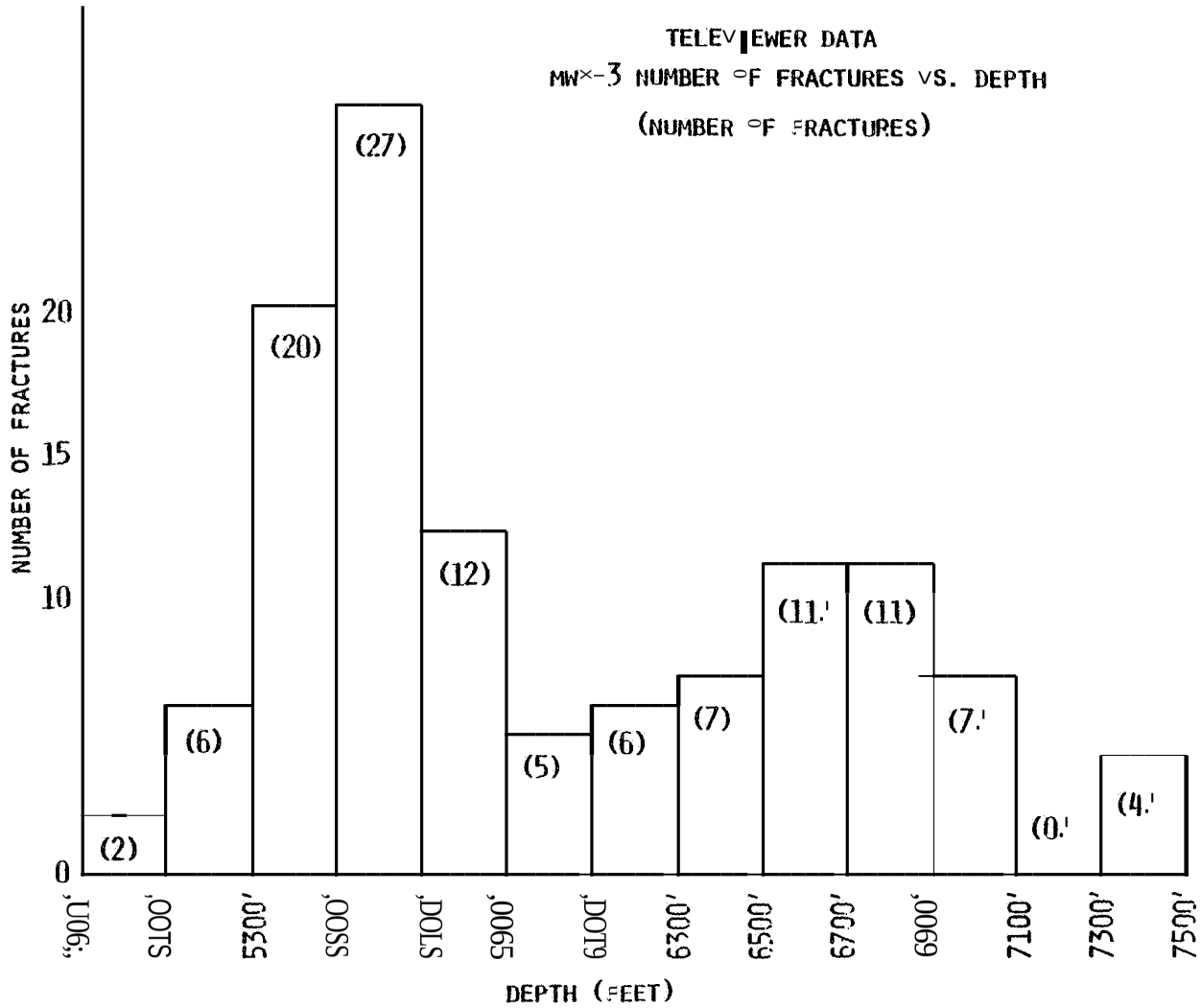
DEPTH (ft)	ZONE
7070-7140	PALUDAL ZONE 3&4
7254-7284	PALUDAL ZONE 2
7854-7894	UPPER COlZETTE
7948-7994	LOWER COZZETTE
8110-8130	CORCORAN

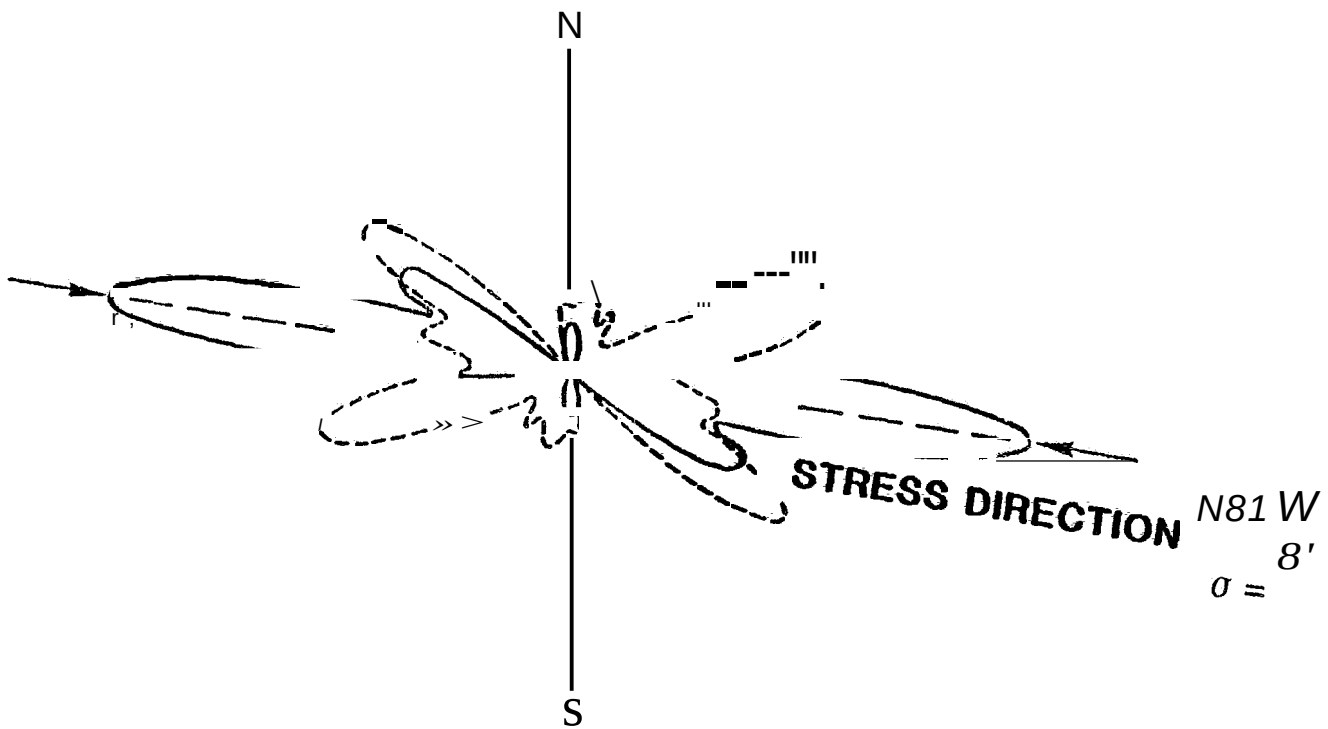


UNCOREOINTERVALS

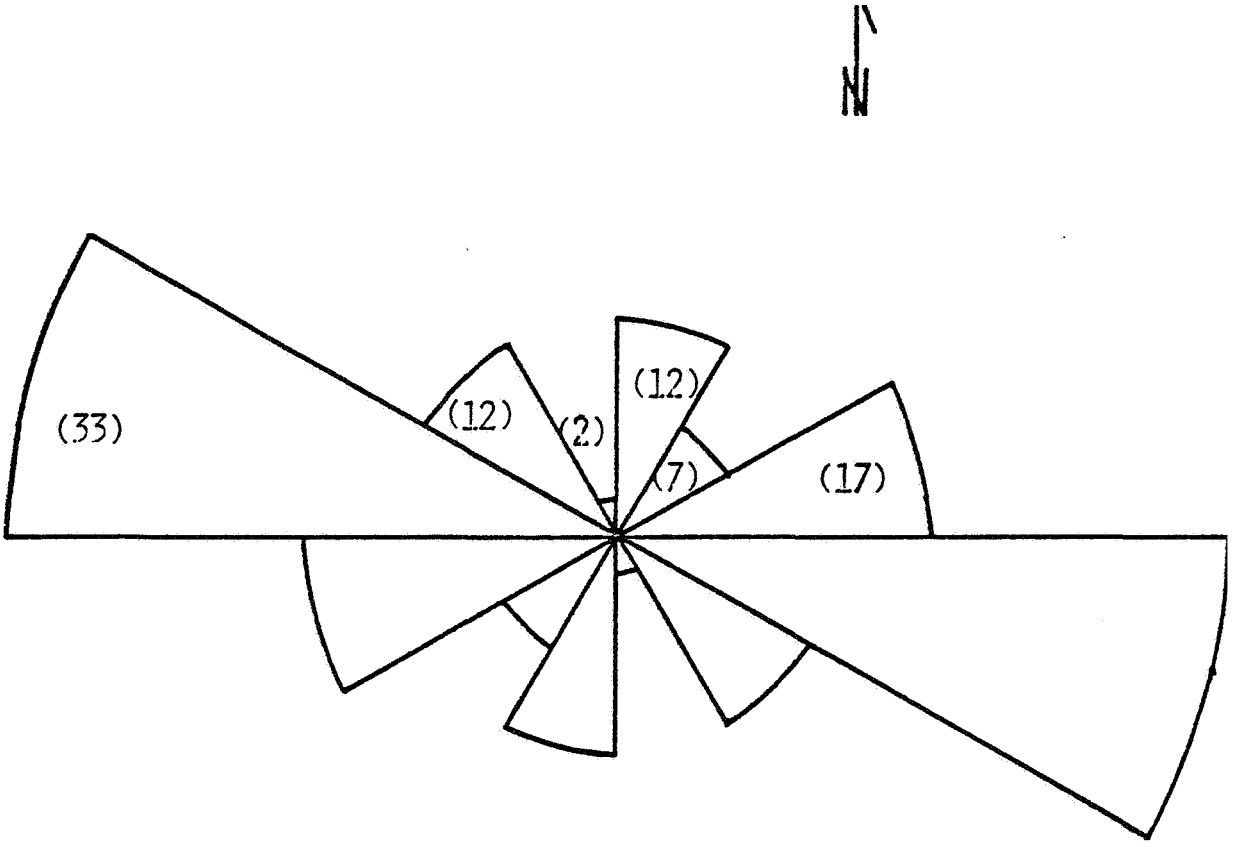


Sandia National Laboratories


TELEVIEWER DATA
MW-3 NUMBER OF FRACTURES VS. DEPTH
(NUMBER OF FRACTURES)
NUMBER OF FRACTURES
0
10
15
20
(2)
(6)
(20)
(27)
(12)
(5)
(6)
(7)
(11)
(11)
(7)
(0)
(4)
4900'
4900'
5300'
5500'
5700'
5900'
6100'
6300'
6500'
6700'
6900'
7100'
7300'
7500'
DEPTH (FEET)



DIRECTIONS OF NATURAL FRACTURES (SOLID LINE)
TI-IE DIRECT ION OF FRACTURE S FROM OUTCROPS IS SHOWN.

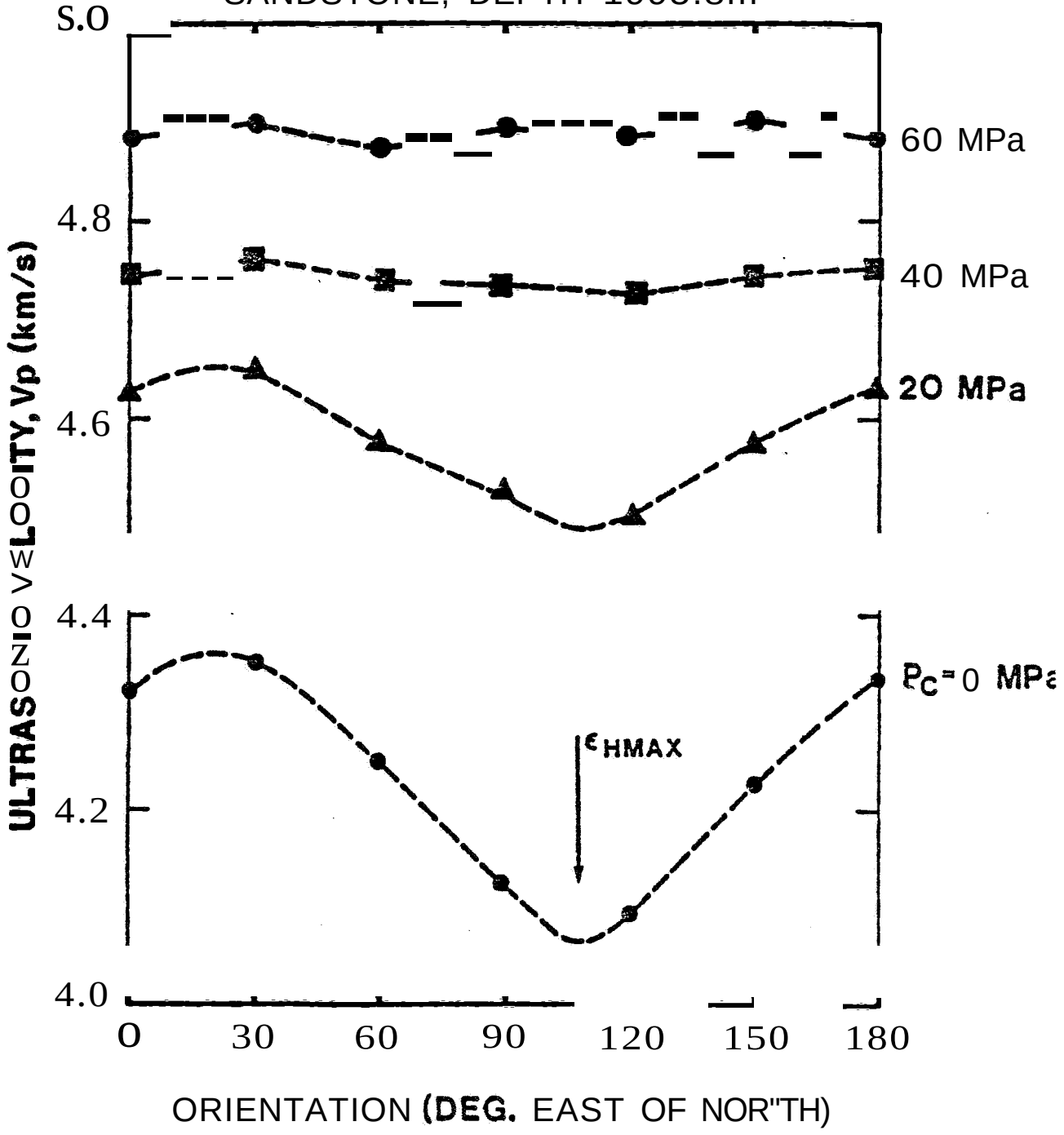


ROSE DIAGRAM OF Mwx-3 FRACTURE AZIMUTHS
IN 30° INTERVALS FROM TRUE NORTH(I)°)
(NUMBER OF FRACTURES)

	TYPE	MAXIMUM STRESS DIRECTION	a	REMARKS
USGS--LINEAMENTS AND FAULTS	SURFACE	N65°-800W	7°	CONJUGATE SHEAR
SANDIA--SURFACE FRACTURES	SURFACE	N79°W	8°	
SANDIA--CORE FRACTURES IN SANDSTONE	CORE	N81°W	15°	
SANDIA--STRAIN RELAXATION	CORE	N75°W	12°	ROTATION
DOWELL--DIFFERENTIAL STRAIN ANALYSIS	CORE	N82°W		MINIMUM VELOCITY
METC-- VELOCITY	CORE	N80°-90°W		
SANDIA--TOPOGRAPHY	CALCULATION	N78°W N600W		4000 FT 8000 FT
MOBIL/SANDIA TELEVIEWER	LOG	N74°W		
SANDIA	HYDRAULIC FRACTURE	N67°W		7100 PT

IN SITU ISOTROPIC CASE-RELAXATION CRACKS

SANDSTONE, DEPTH 1995.8m



SUMMARY COMPARISON OF MINIMUM HORIZONTAL STRESS MAGNITUDE AT MWX SITE, RIFLE, COLORADO: DEPTH 7874-7940 ft.

MINI-FRAC (3)	48 ± 1 MPa
STRAIN RECOVERY (3)	44 ± 4 MPa
DIFFERENTIAL STRAIN (2)	51 ± 5 MPa

BLWEW

SUMMARY COMPARISON OF MAXIMUM HORIZONTAL STRESS DIRECTION DETERMINED FROM ORIENTED CORe TECHNIQUES FOR MWX SITE, RIFLE, COLORADO: DEPTH 1420-2475m

	RANGE	MEAN
STRAIN RECOVERY MEASUREMENTS (62 cores)	85 -135	105 ± 15
DIFFERENTIAL STRAIN ANALVSIS (6 cores)	75 - 119	98 ± 12

RECOVERY OF PRESSURE CORE

TARGET SANDS WERE LENTICULAR SANDS 15-30 FEET THICK

ONLY THREE IS-FoOT PRESSURE CORE BARRELS COULD BE .. EMPLOYED

WE WANTED TO FILL ALL BARRELS WITH SAND

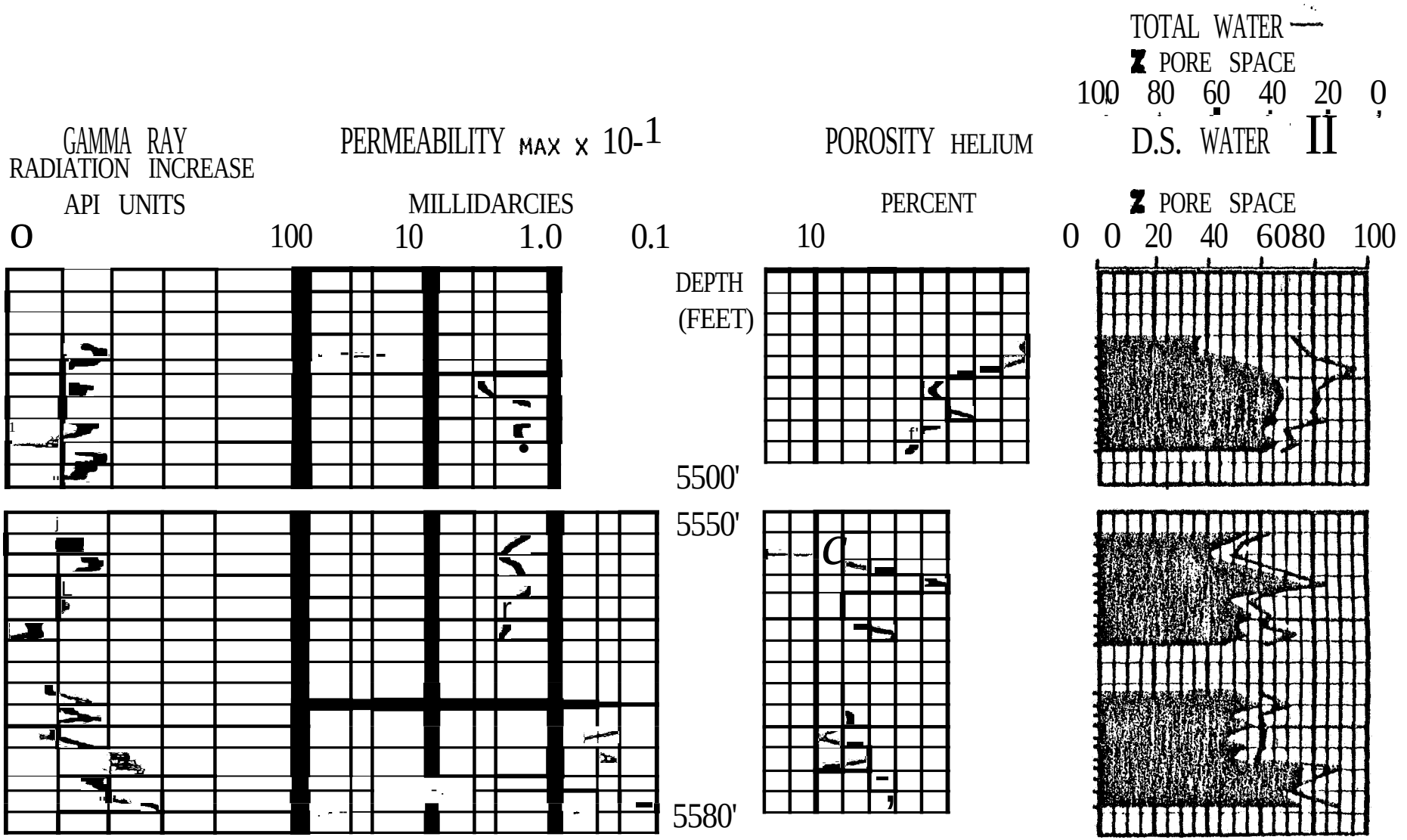
WELL CONTROL AVAILABLE 12S FEET AWAY

SPECIAL LOGGING RUN MADE TO WITHIN 50 FEET OF Top SAND

TARGET LENSES HIT • • • ALL PRESSURE CORE BARRELS FILLED WITH SAND

ONE PRESSURE CORE BARREL FAILED--CORE STILL FROZEN AND PRESERVED FOR SIDE BY SIDE ANALYSES OF PRESSURE AND "NORMAL" CORE

"NORMAL" AND PRESSURE CORE ANALYSIS SHOW LITTLE DIFFERENCE IN WATER SATURATION FOR SIMILAR POROSITIES


GAMMA RAY
RADIATION INCREASE
API UNITS
O
PERMEABILITY MAX x 10-1
MILLIDARCIES
100
10
1.0
0.1
DEPTH
(FEET)
5500'
5550'
5580'
POROSITY HELIUM
PERCENT
10
TOTAL WATER
% PORE SPACE
100 80 60 40 20 0
D.S. WATER
% PORE SPACE
0 0 20 40 6080 100

CAUSES OF DISCREPANCY IN WATER SATURATION VALUES

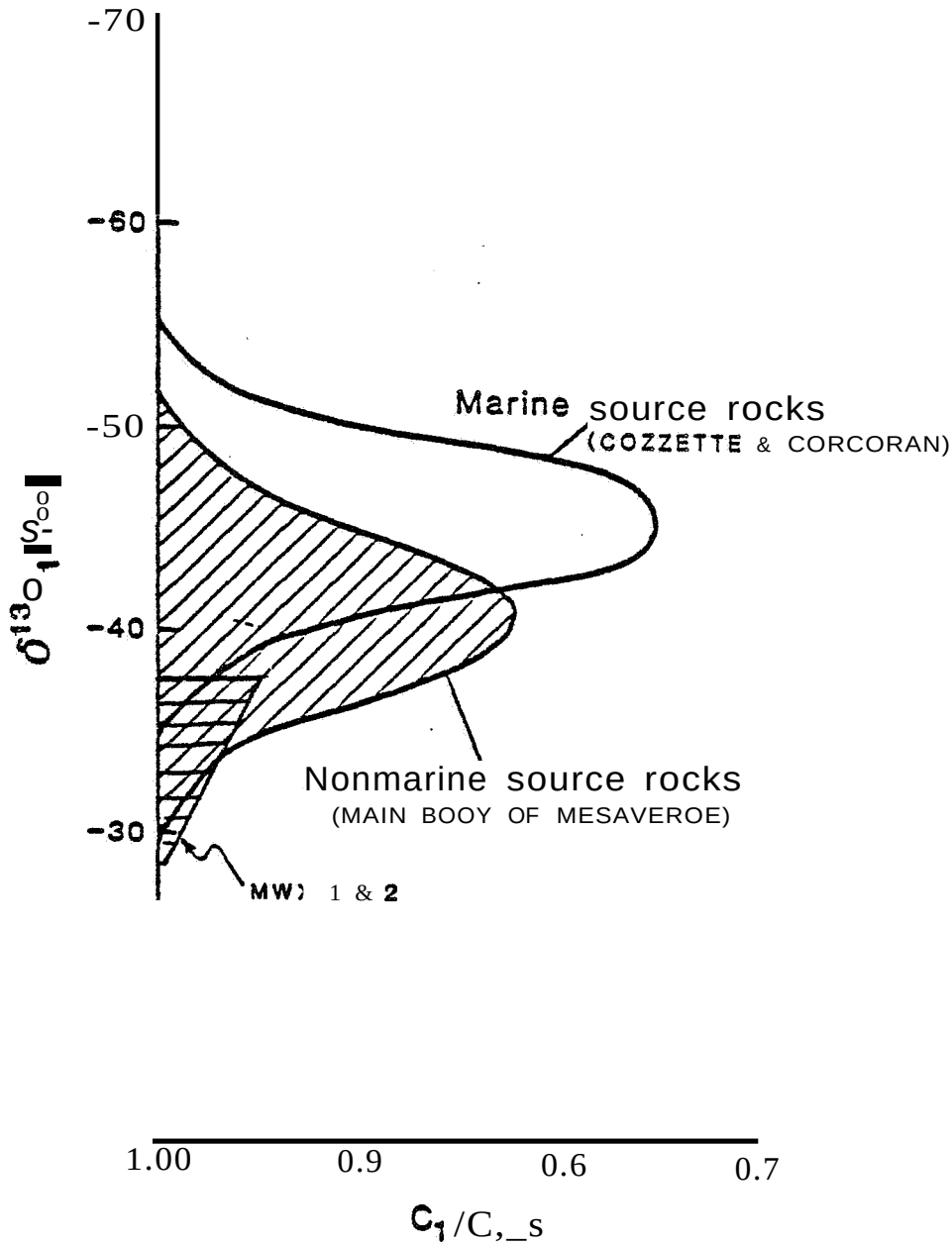
1. ORGANIC FLUIDS INVADING CORE
2. CLAY BOUND WATER
3. EXTREMELY TIGHT ROCK

ESTIMATE OF GAS IN PLACE

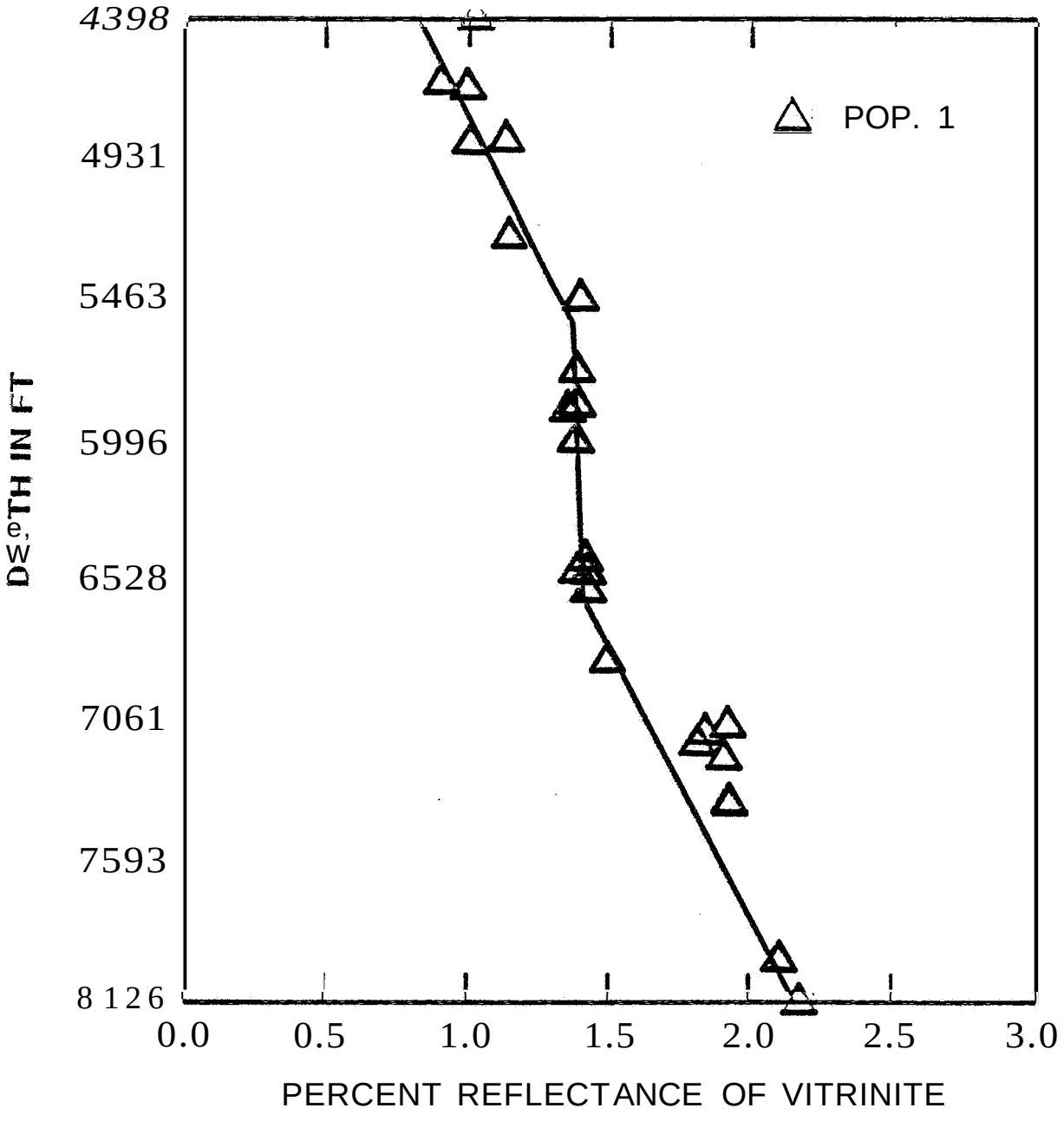
CALCULATE AND COMPARE IN SITU PORE PRESSURES

1. FROM GAS CAPTURED FROM PRESSURE CORE SAMPLES, ϕ, S_W

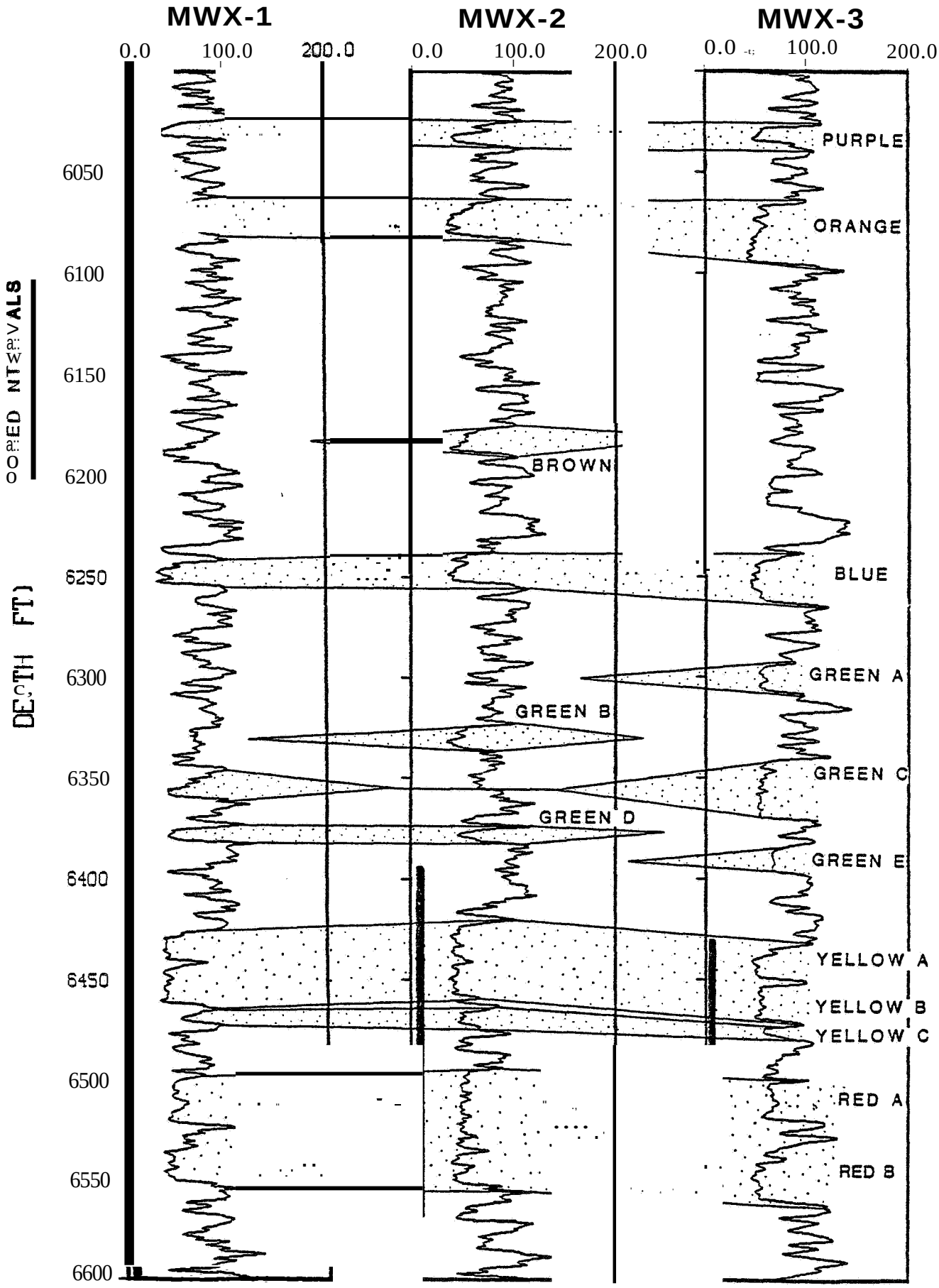
2. FROM HYDROSTATIC PRESSURE OF DRILLING FLUID REQUIRED TO MAINTAIN EQUILIBRIUM DURING DRILLING.



Chemical & Isotopic Analysis of **Gas** from MW X Core


4398
4931
5463
5996
6528
7061
7593
8126
DEPTH IN FT
POP. 1
0.0
0.5
1.0
1.5
2.0
2.5
3.0
PERCENT REFLECTANCE OF VITRINITE

COASTAL ZONE



CONCLUSIONS

RESERVOIR PARAMETER DATA

- ROUTINE ANALYSES ACROSS SANDS THROUGHOUT MESAVERDE.
- SPECIAL PERMEABILITIES (DRY) ACROSS ZONES OF INTEREST.
- RELATIVE PERMEABILITIES AND CAPILLARY PRESSURES IN ZONES OF INTEREST.
- WATER SATURATION FROM PRESSURE CORE DATA.

STRESS AND ROCK MECHANICS PROPERTIES

- MECHANICAL PROPERTY ANALYSES IN ZONES OF INTEREST.
- ORIGINS AND STUDIES OF NATURAL FRACTURES.
- HYDRAULIC FRACTURE DESIGN.
- HYDRAULIC FRACTURE AZIMUTH PREDICTION.

CONCLUSIONS (CONT'D)

GEOLOGIC ANALYSES

- MINERALOGY} SEDIMENTOLOGY ACROSS MESAVERDE; EMPHASIZED IN ZONES OF INTEREST.
- PALEOPRESSURE AND PALEOTEMPERATURE MODELS.
- EVALUATION OF COALS AND ORGANIC MATERIAL.
- ORIGIN OF GAS IN MESAVERDE.

HYDRAULIC FRACTURE DESIGN

- FORMATION DAMAGE.
- DECOMPOSITION OF FRACTURE FLUIDS.
- PROPPANT EMBEDMENT.

CORE-LOG CORRELATIONS

- CORRELATIONS BEING OBTAINED ON SIMPLE} EMPIRICAL} AND ADVANCED LEVELS.

FUTURE MWX CORE ANALYSIS

COMPLETE RESERVOIR PARAMETER AND ROCK PROPERTY ANALVSES OF CORE FROM ZONES TO BE STIMULATED.

UVDRAULIC FRACTURE DESIGN

- CORE ANALYSES PERFORMED BV SERVICE COMPANIES AND OTHER LABORATORIES ON A ZONE-BV-ZONEBASIS.
- TEST EFFECTS OF ALCOHOL-SURFACTANT TREATMENTS ON CORE.
- ASSIST) IF APPROPRIATE) IN DEVELOPMENT OF A DELAYED BREAKER.

FUTURE MWX CORE ANALYSIS (CONT'D)

ROCK MECHANICS AND STRESS

TEST OF NET STRESS HYPOTHESIS.

TEST OF CONCEPT OF PORE PRESSURE IN SHALES.

FAILURE ENVELOPE STUDY FOR ORIGIN OF NATURAL FRACTURES.

ORGANIC MATURATION--COMPLETE ANALYSES OF MWX CORE (ORGANIC CONTENT) PYROLYSIS),

COMPLETE ANALYSES OF PALUDAL COALS (RESERVOIR PARAMETERS) ROCK PROPERTIES} EMBEDMENT).

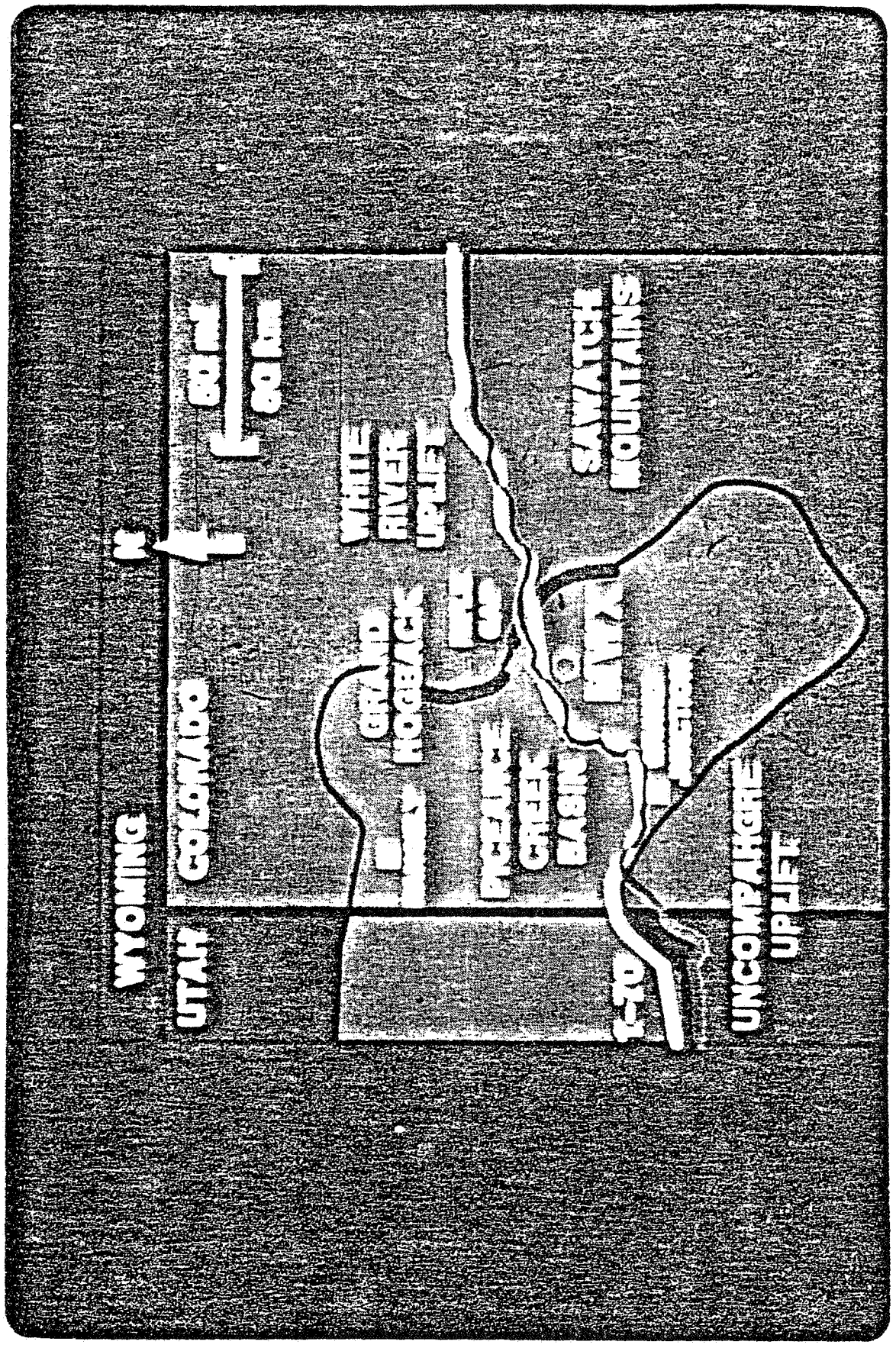
Studies of the Sedimentology and Natural Fractures of the Mesaverde Rocks at the MWX Site and Environs

Geotechnology Research Division 6253,
Sandia National Labs

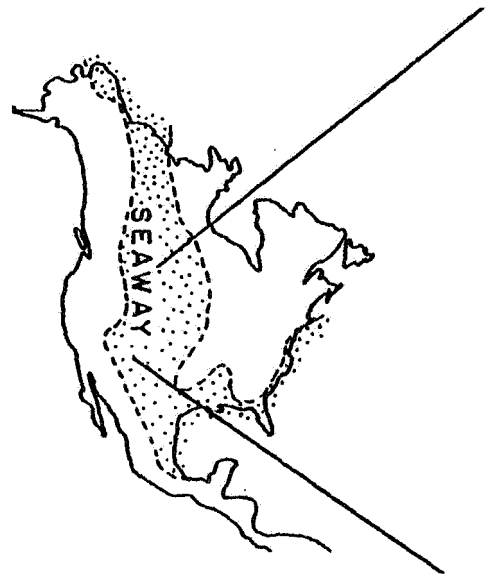
John C. Lorenz

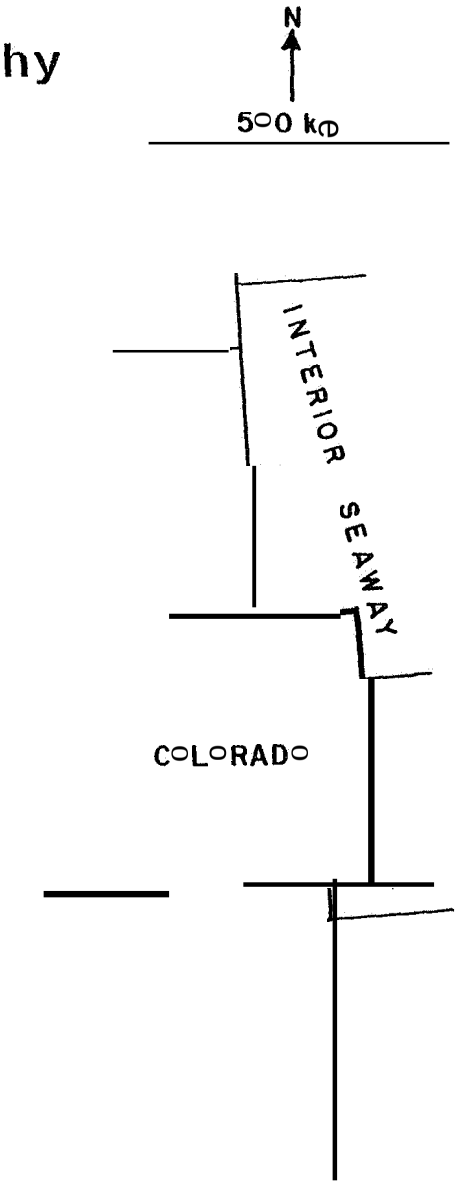
Period of Performance: Continuing

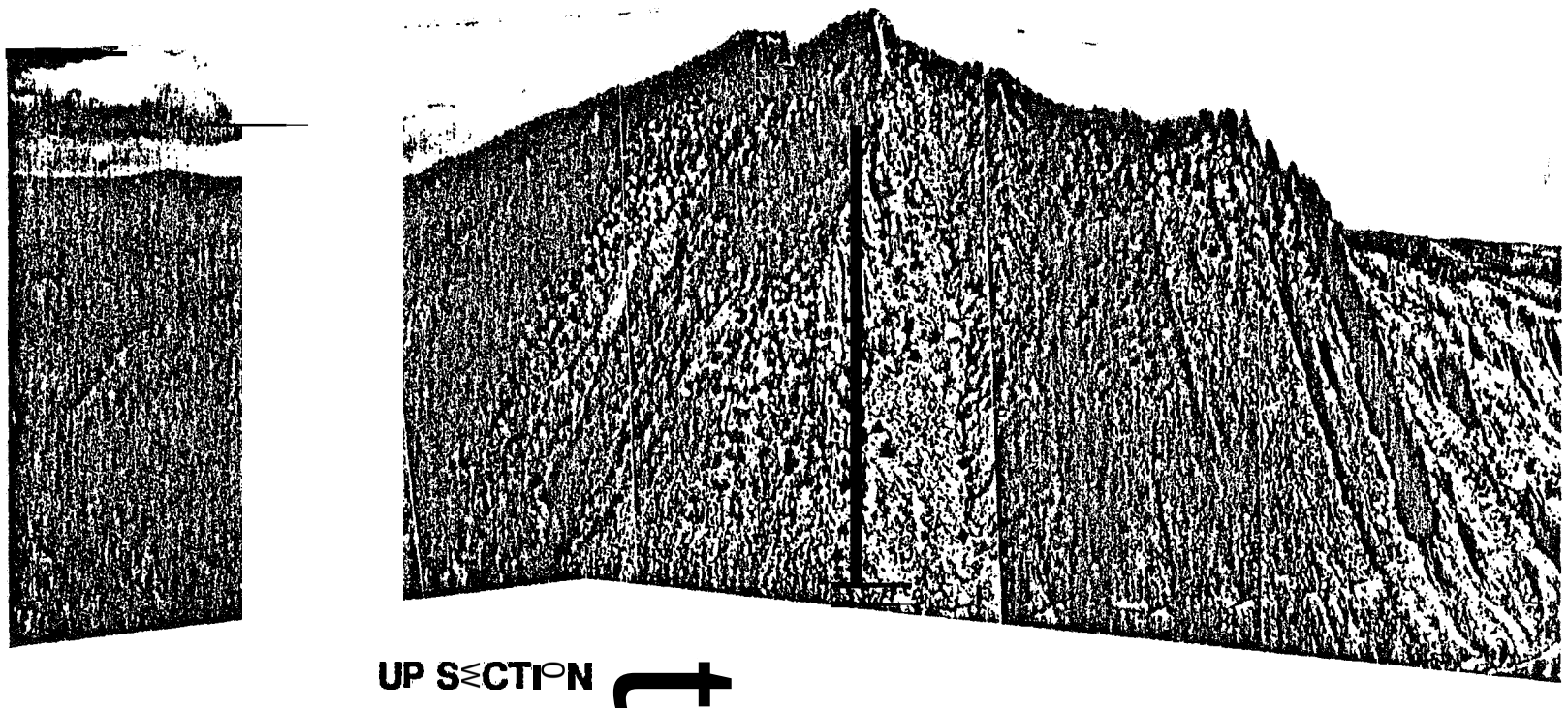
Contract Funding: Part of MWX, approx.2 FTE


WYOMING
UTAH
COLORADO
GRAND HOGBACK
WHITE RIVER UPLIFT
UNCOMPAHGRE UPLIFT
SAWATCH MOUNTAINS

Cretaceous Paleogeography

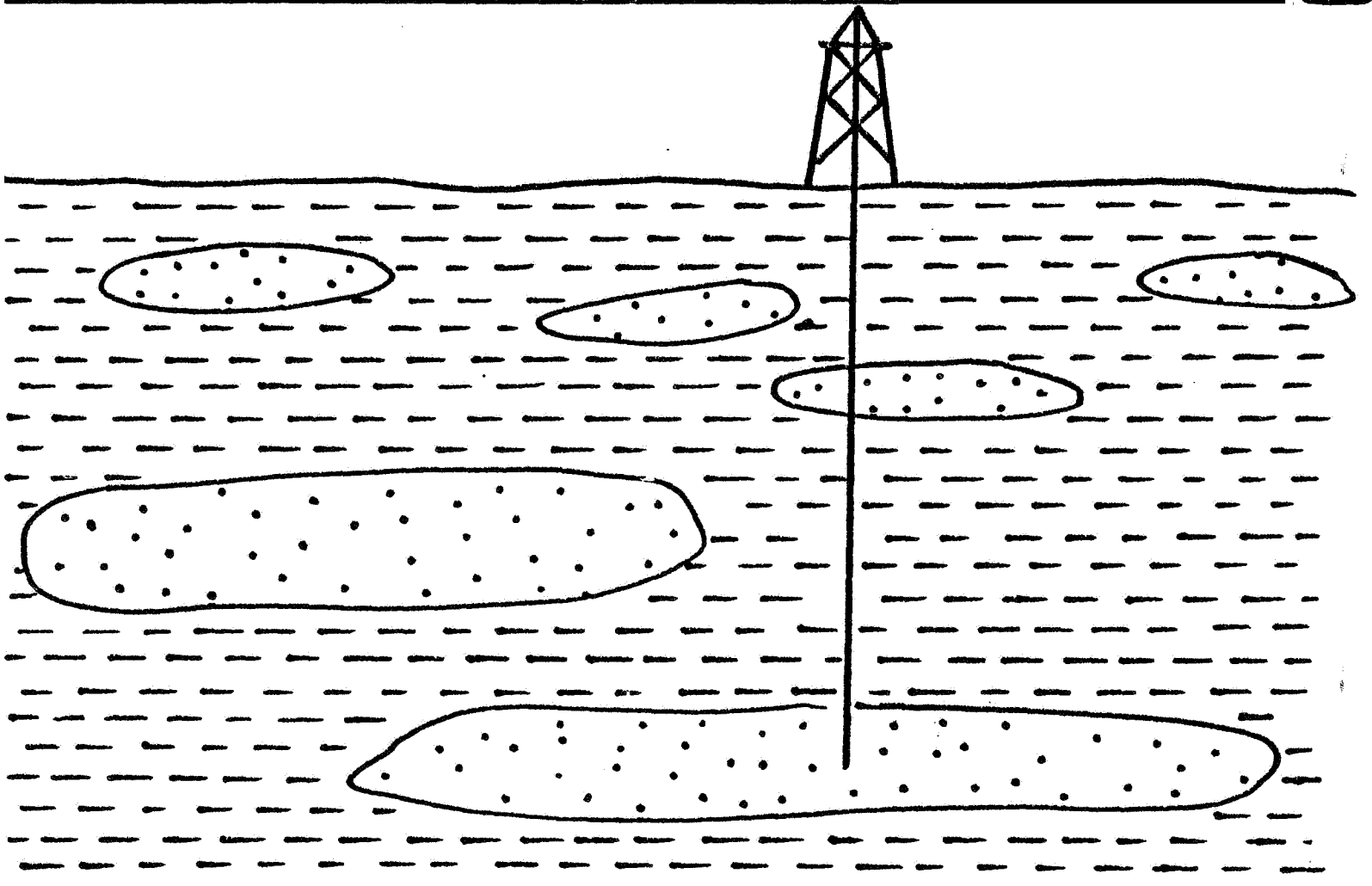




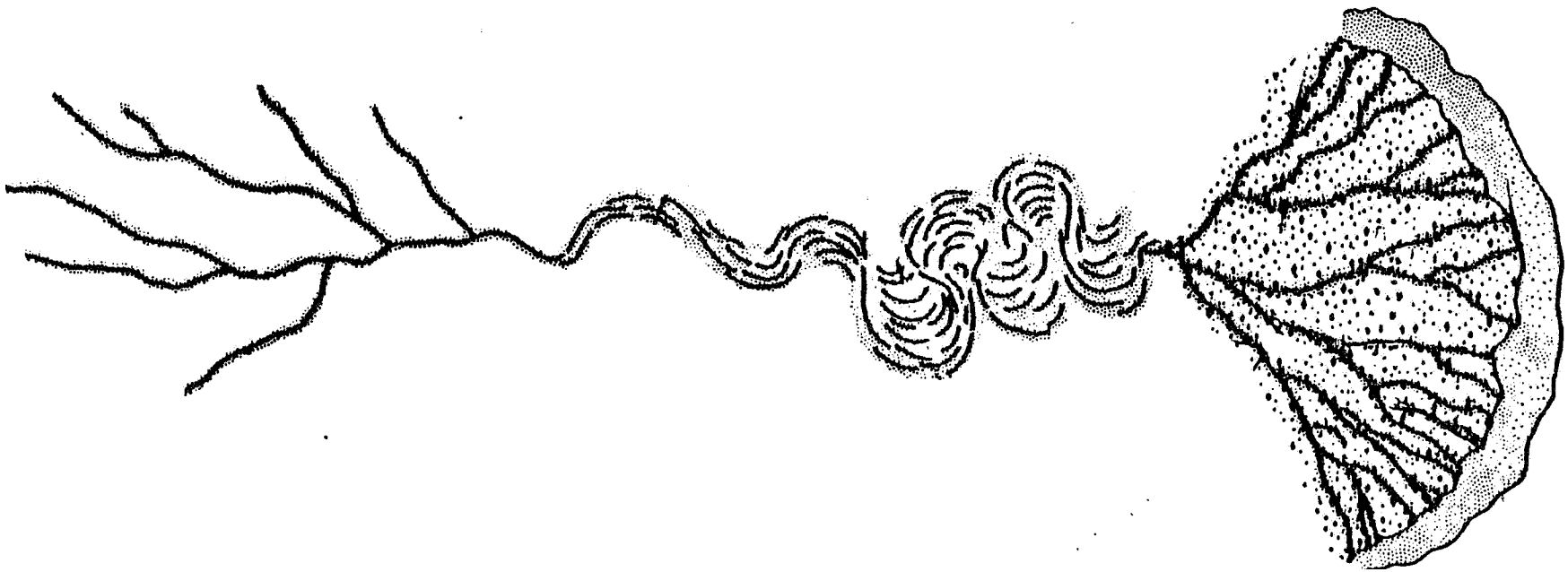


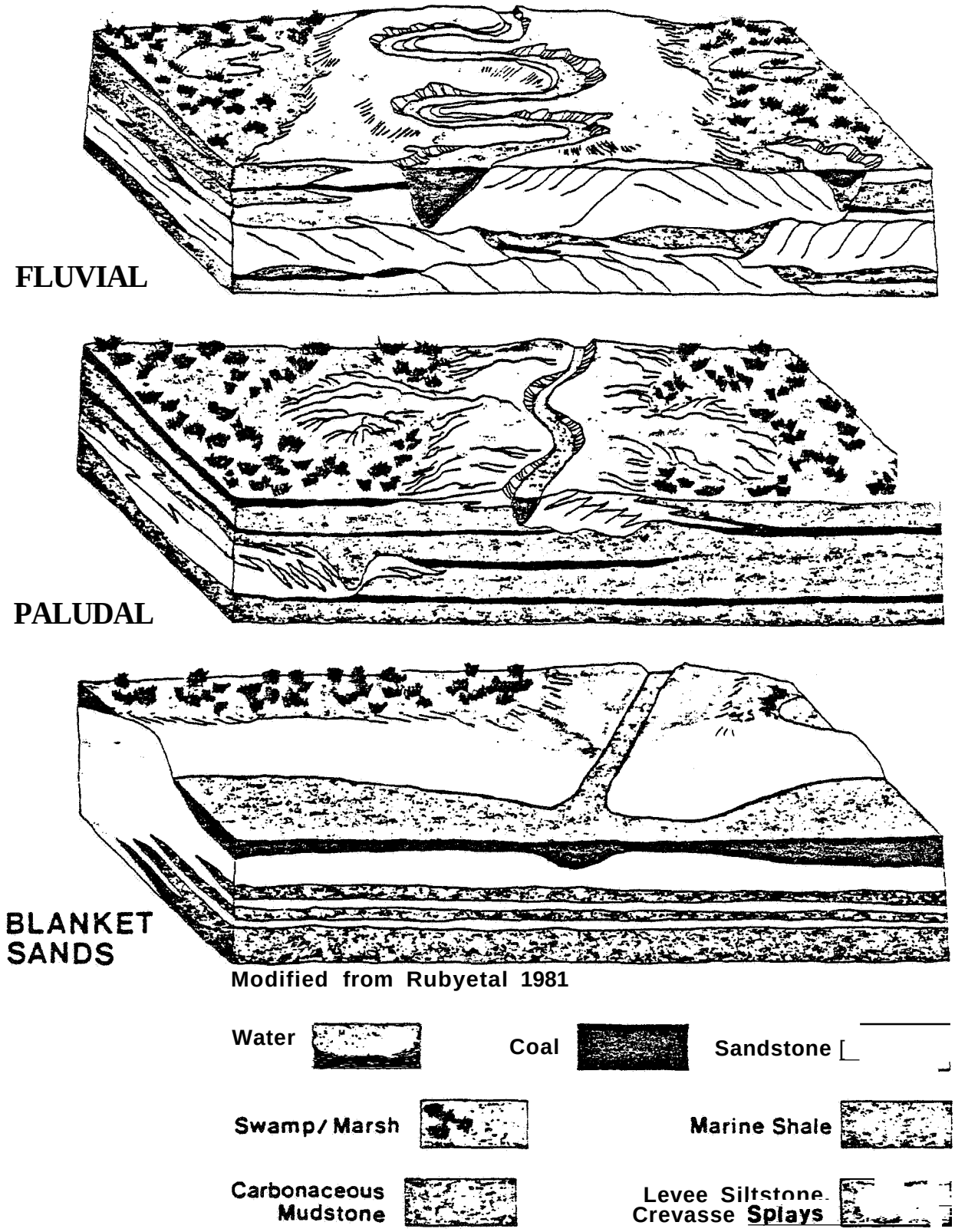
Complete Mesaverde Section East Side Rifle Gap

Reservoir Shape and Size from Single-Well Data



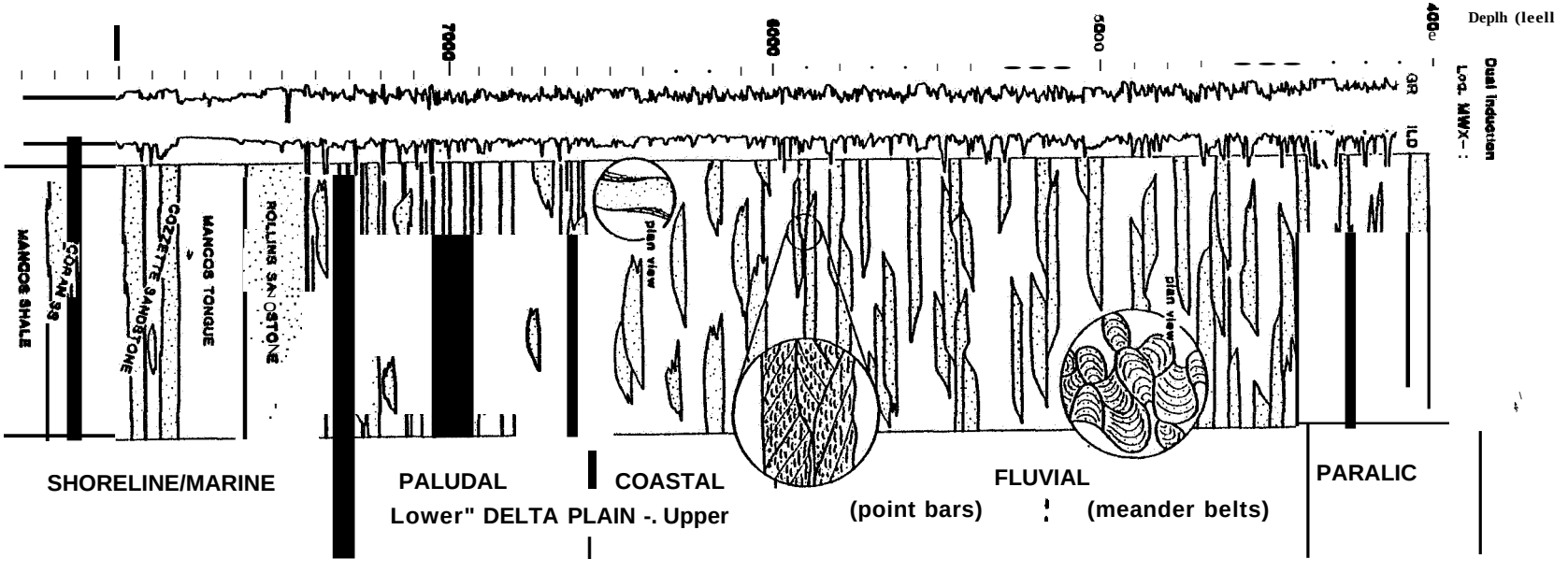
Different Environments Deposit Different Types of Reservoirs



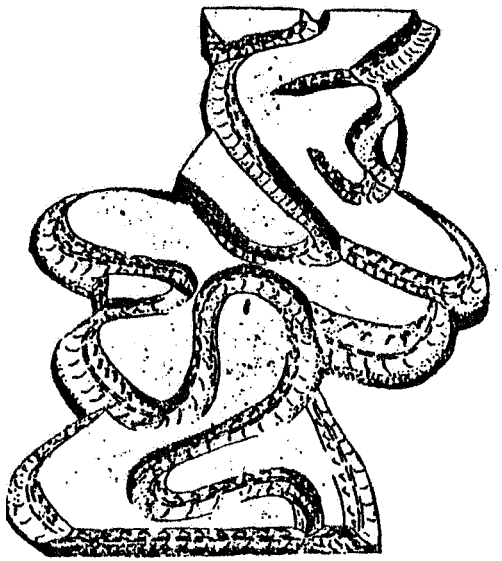


Modified from Rubyetal 1981

Reservoir Morphologies at theMWX Site



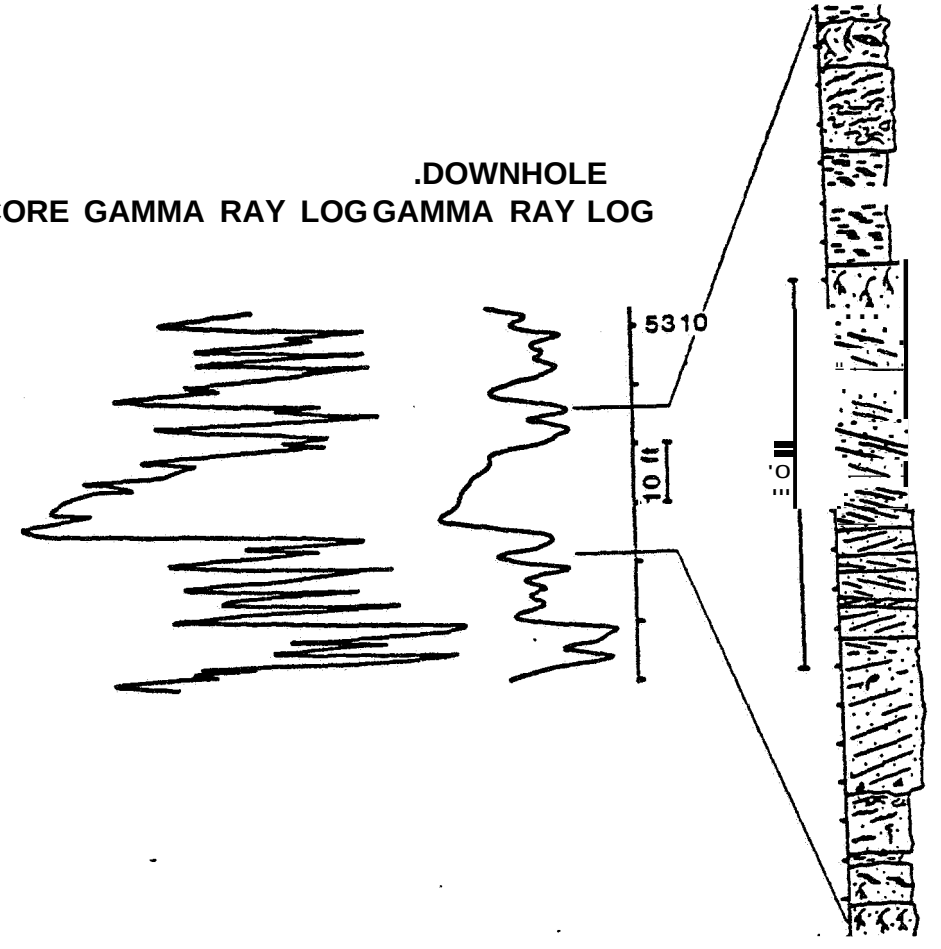
Meander Belt Reservoir Morphology



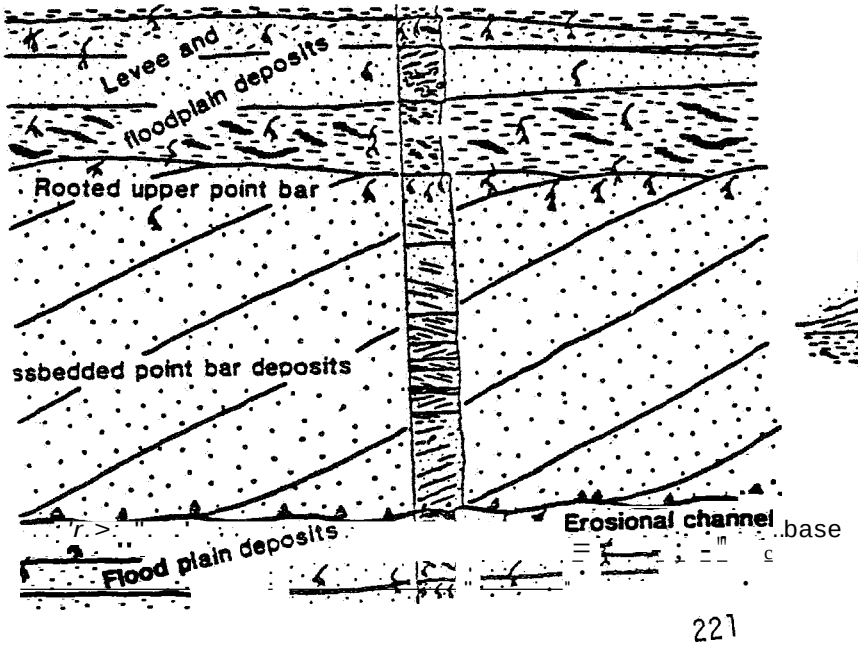
CORE LITHOLOGY LOG

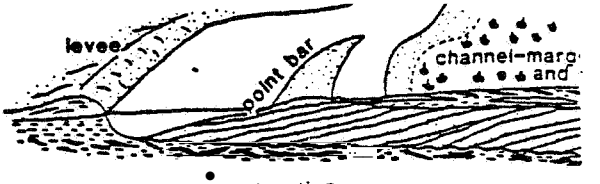
.DOWNHOLE

CORE GAMMA RAY LOG GAMMA RAY LOG

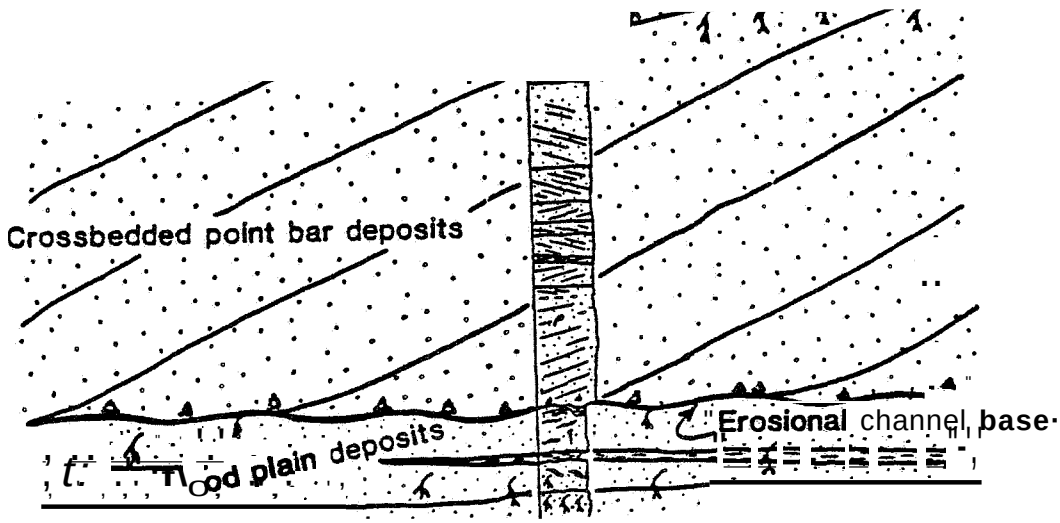


INTERPRETATION

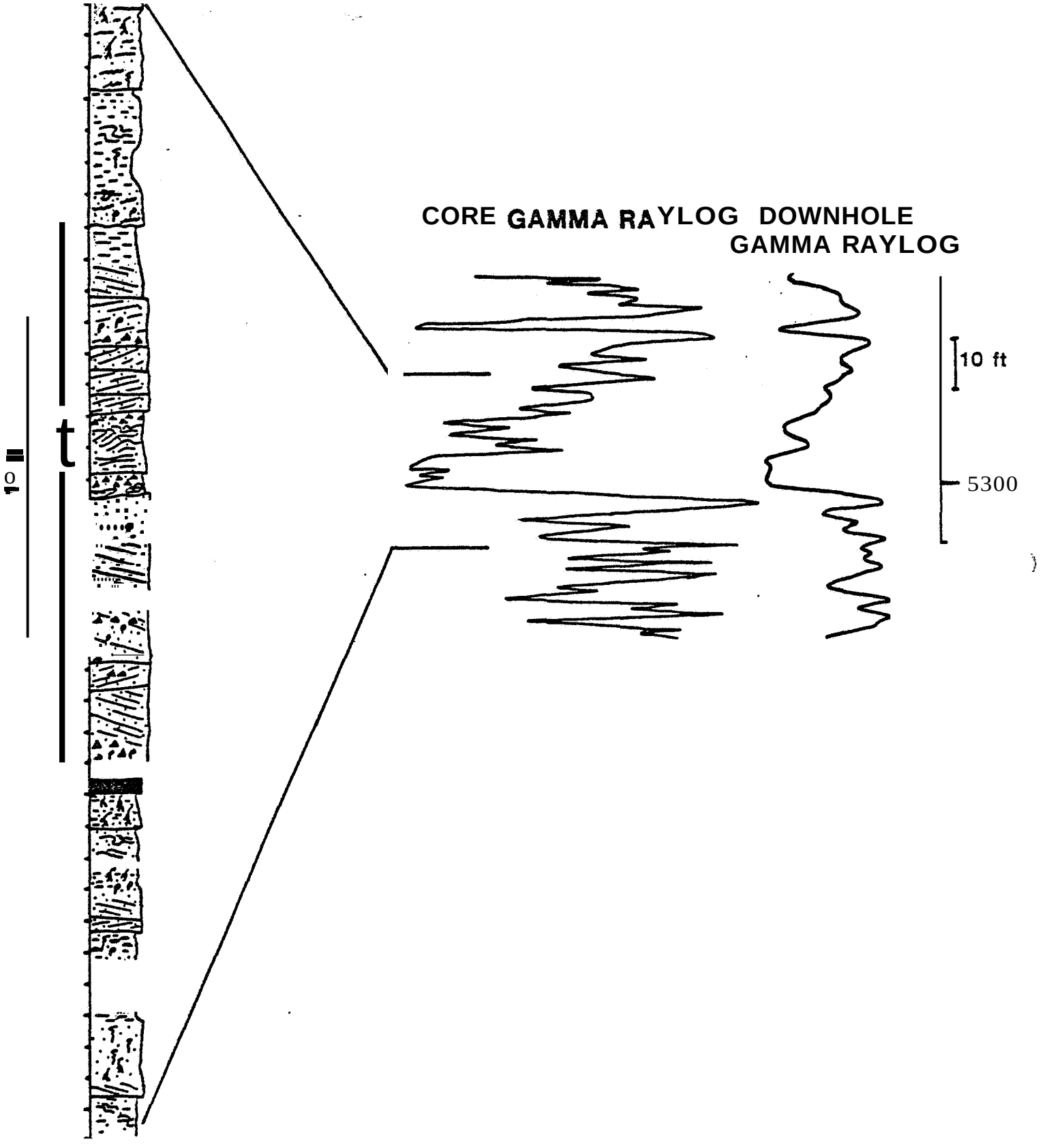


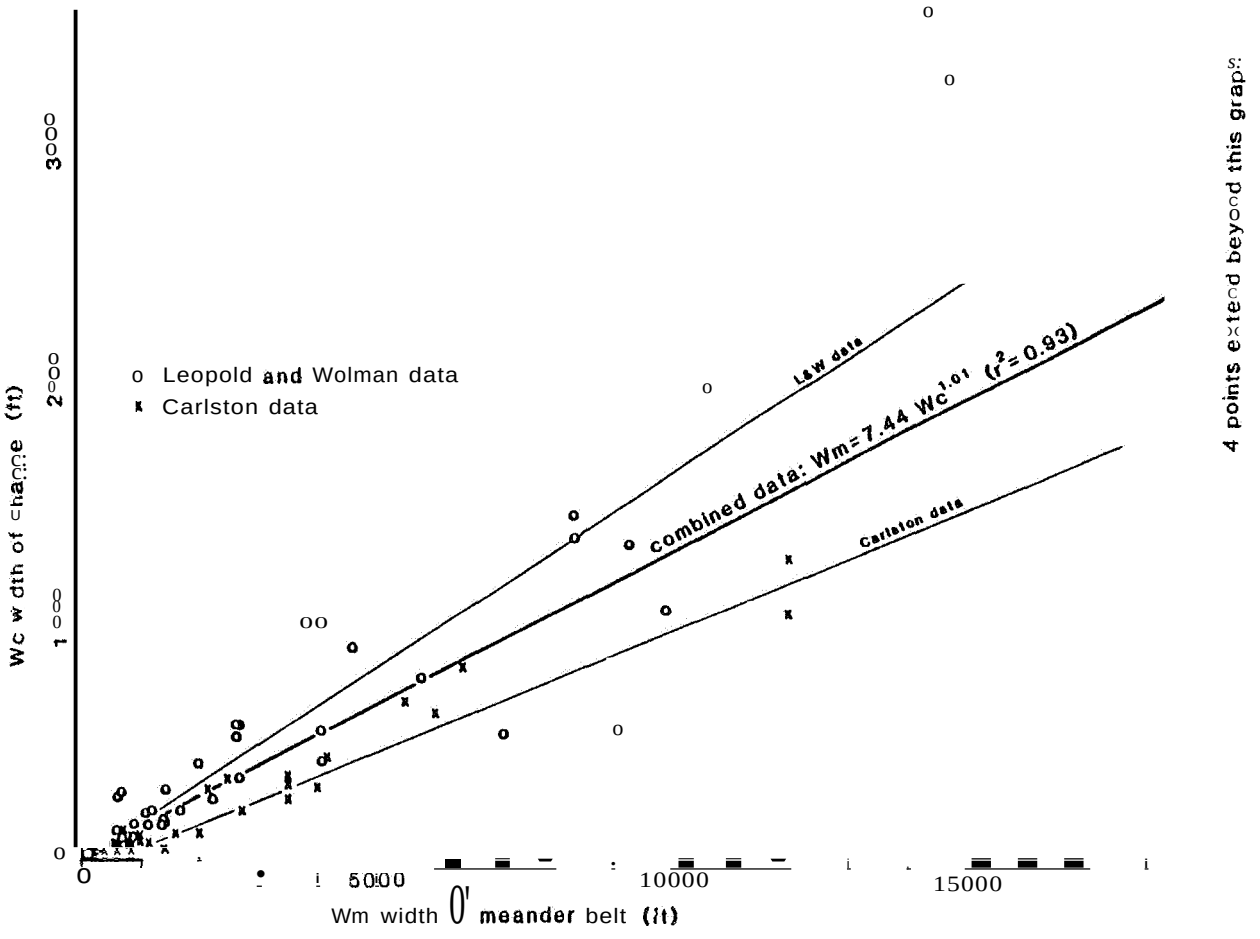


adapted from Miall, 1979

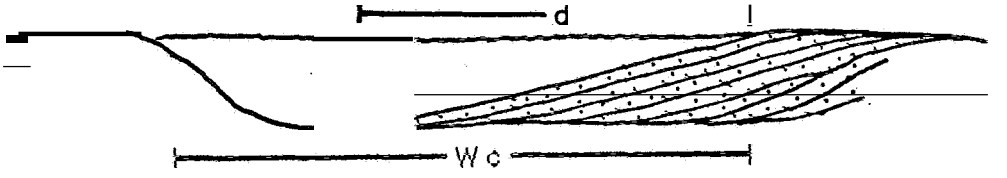

Crossbedded point bar deposits
Erosional channel base
Flood plain deposits

CORE LITHOLOGY LOG

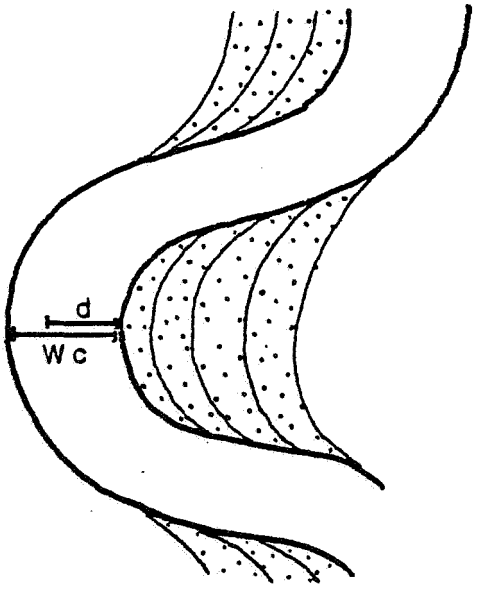




Conversion of Channel Width To an Estimate of Reservoir Width

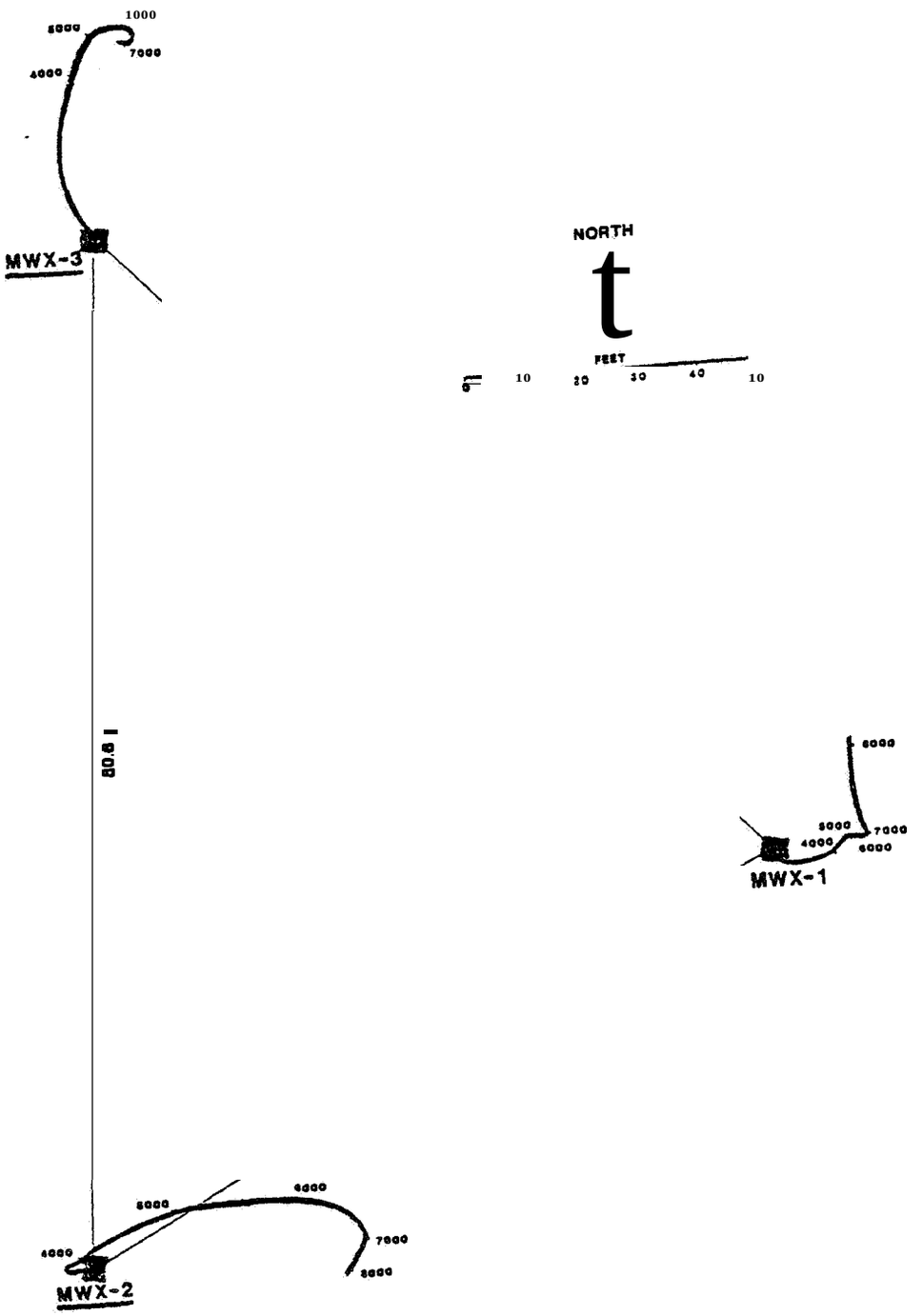


WC=1.5d

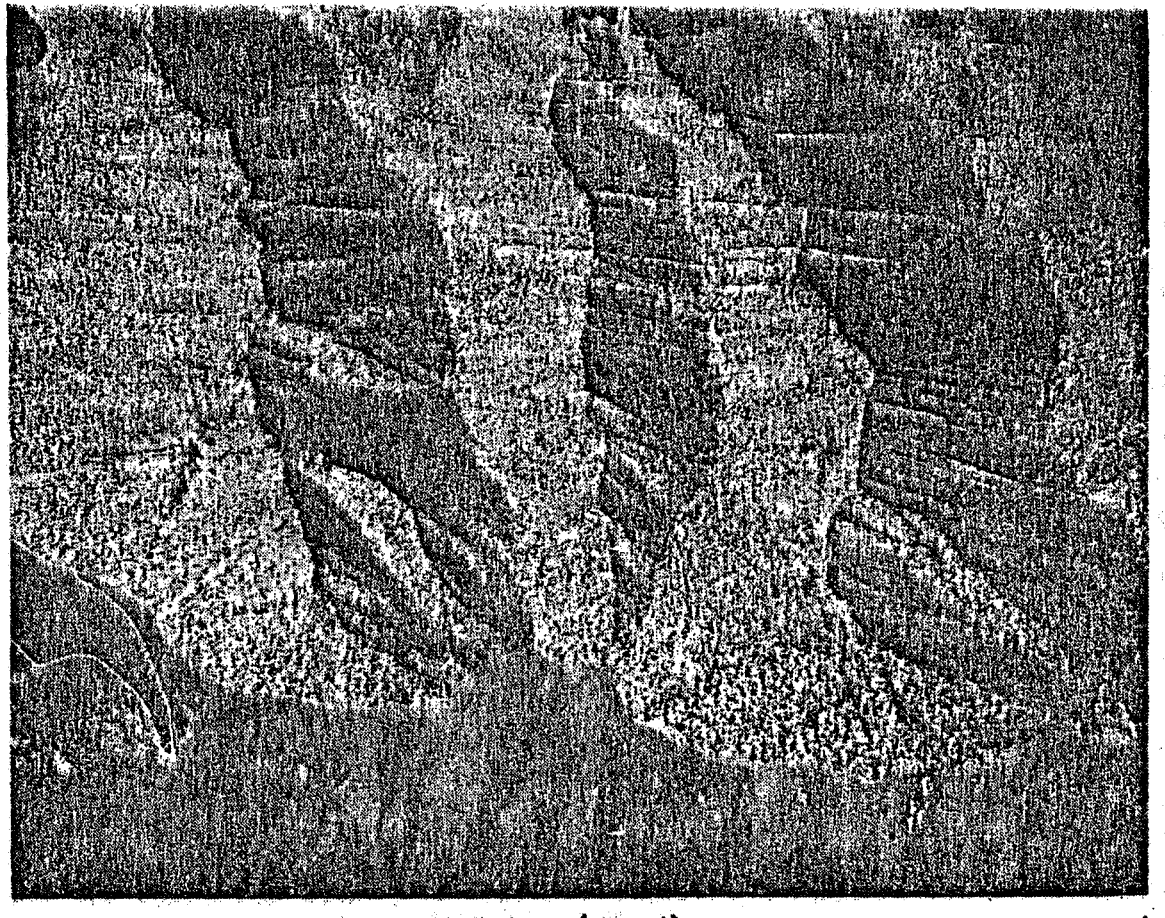


Point Bar Widths Are a Related to Channel Width

Triangular Lavout of the MWX Wells Allows Probability Calculations of Reservoir Widths



Reservo dths Have Been Estimated using Air Photos of Outcrops

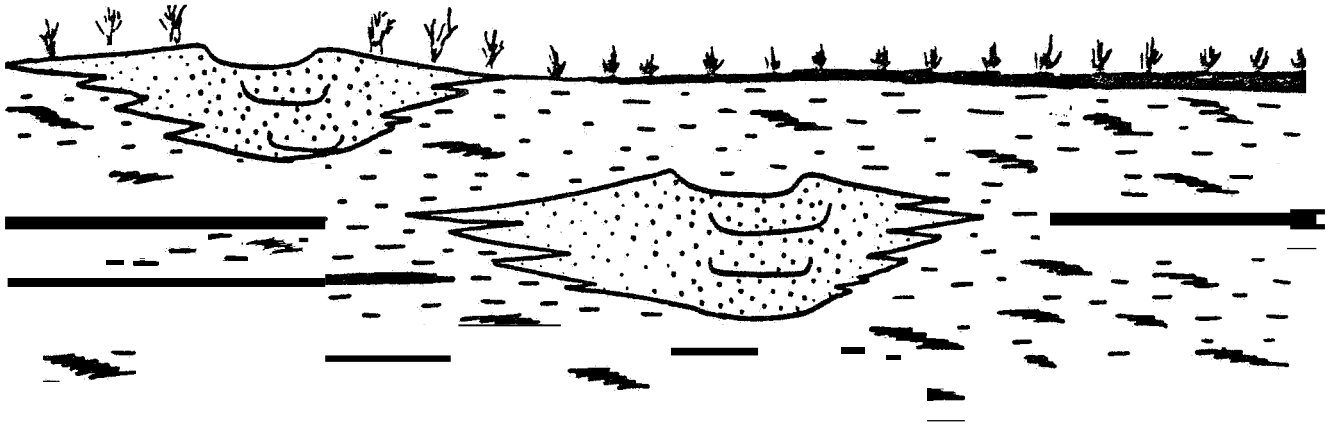


1.6 km (1 mi)

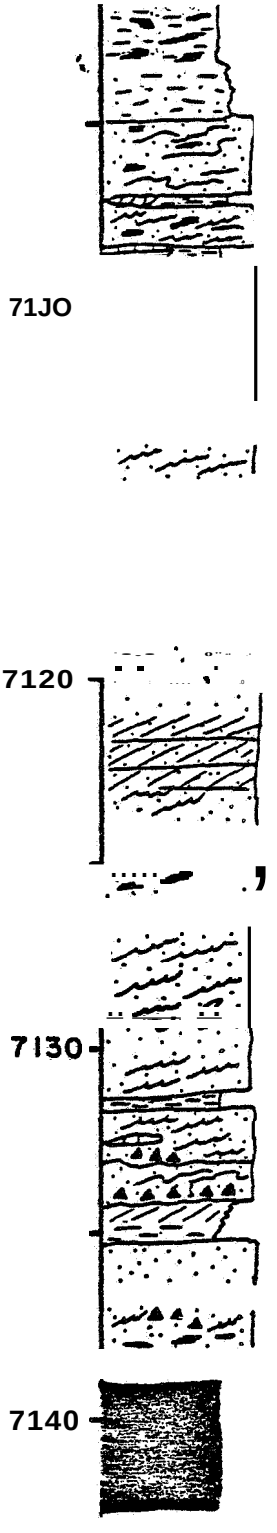
Estimates Have Been Made f6rReservoir Width

	core	probability	outcrop air photos	outcrop sedimentology
paralic	NA	NA	1-2 km	1-2 km
meander belts	350-520 m	125-410 m	>60 m	4.30-650m
delta distributaries	60-170m	40-160 m	NA	NA

·Delta Plain Reservoirs are Lenticular

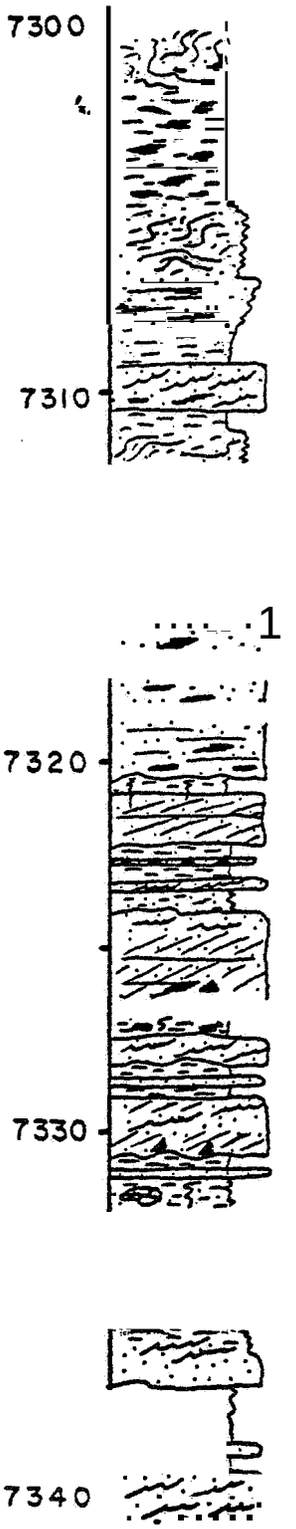


zone 3
main channel



zone 1

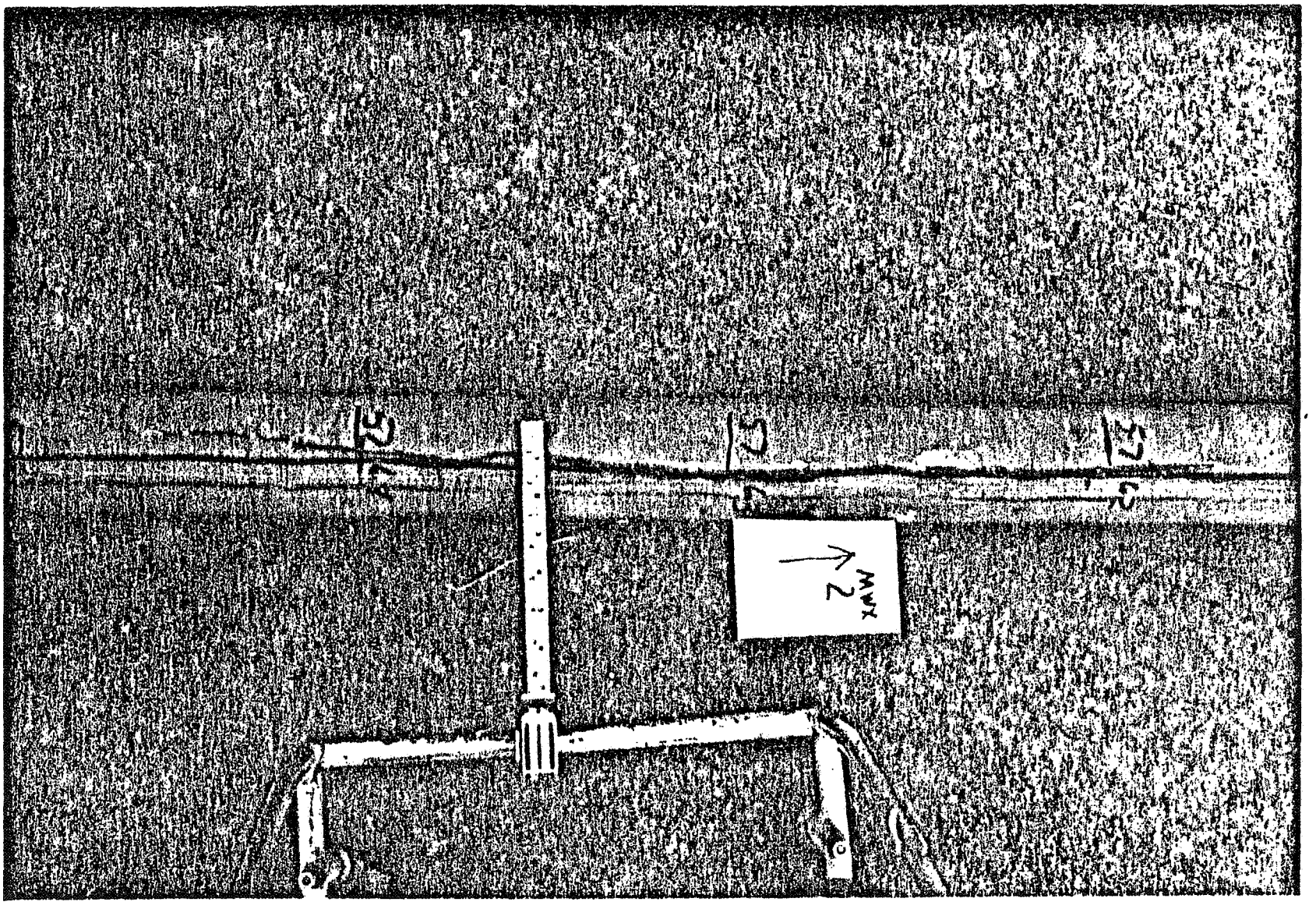
channel margin



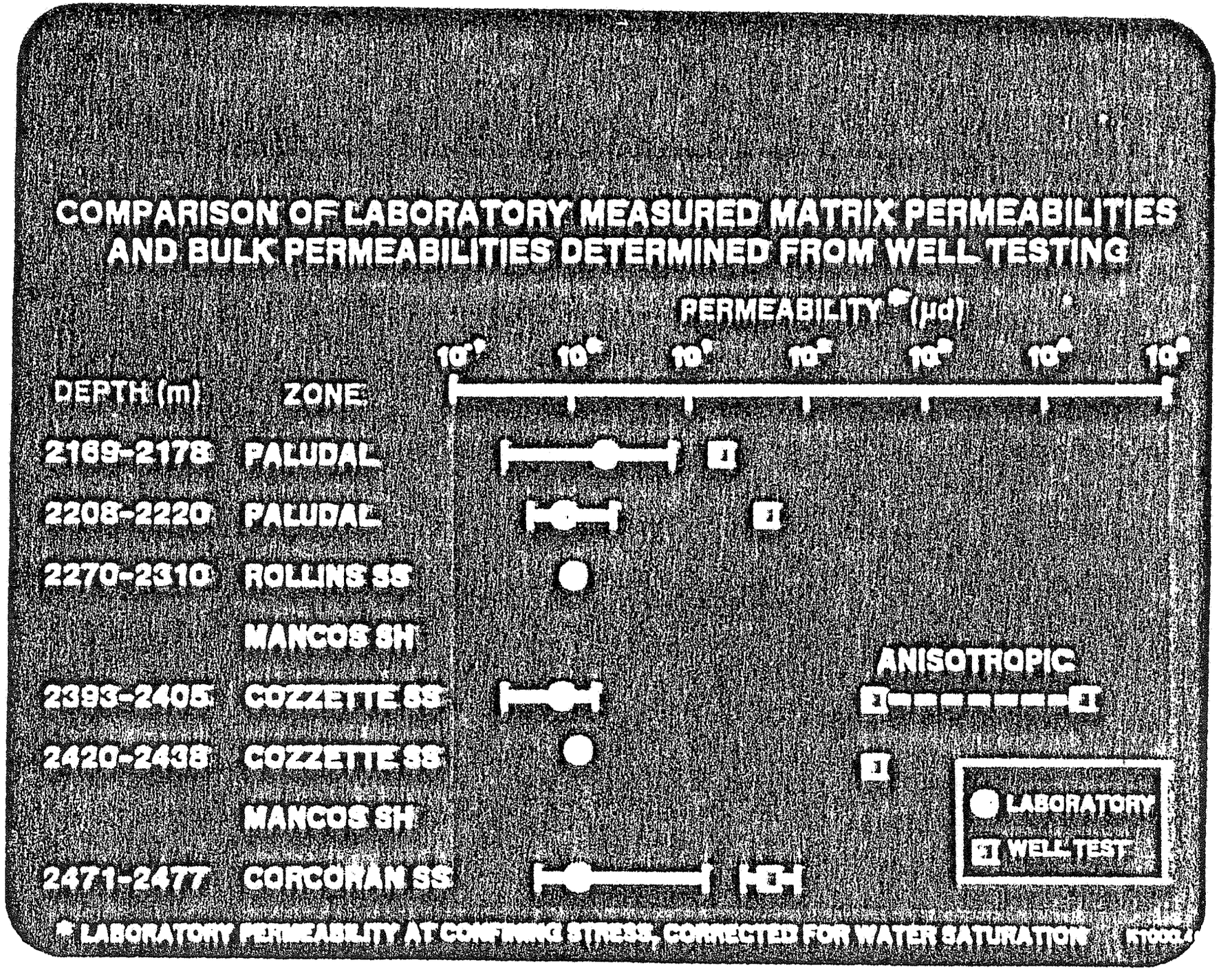
Westmate of Orientation of Lenticular Delta Plain Reservo

Continuing Sedimentological Studies

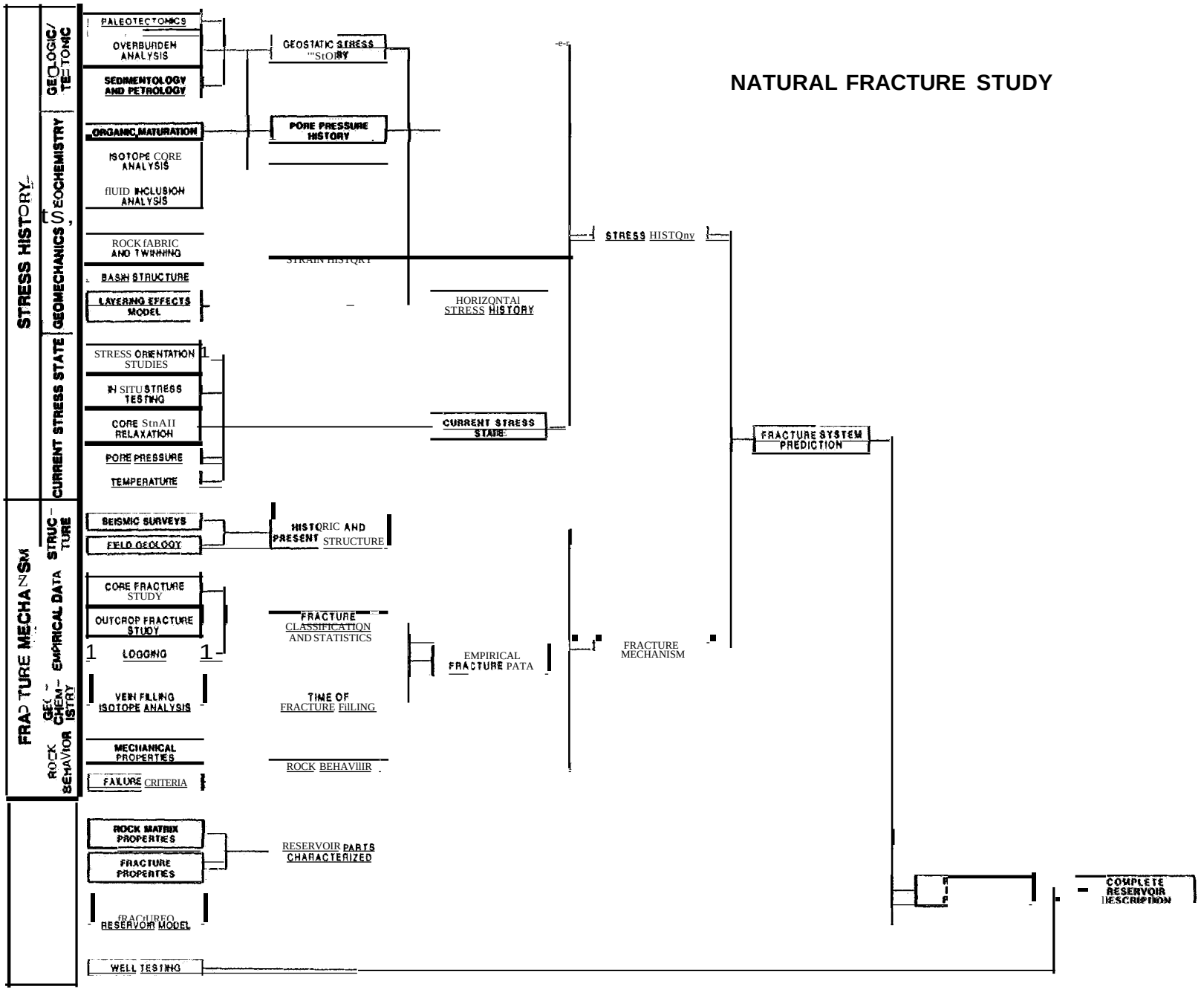
- **Lens-Specific Core Description and Interpretation**
- **3-D Lens Density and Spacing Studies**
- **Grain Sizes Relative to Depositional Environment (UNM)**



Permeability may be Dependant on Fractures


COMPARISON OF LABORATORY MEASURED MATRIX PERMEABILITIES AND BULK PERMEABILITIES DETERMINED FROM WELL TESTING
PERMEABILITY* (μd)
DEPTH (m)
ZONE
2169-2178
PALUDAL
2208-2220
PALUDAL
2270-2310
ROLLINS SS
MANCOS SH
2393-2405
COZZETTE SS
2420-2438
COZZETTE SS
MANCOS SH
2471-2477
CORCORAN SS
ANISOTROPIC
LABORATORY
WELL TEST
* LABORATORY PERMEABILITY AT CONFINING STRESS, CORRECTED FOR WATER SATURATION

NATURAL FRACTURE STUDY



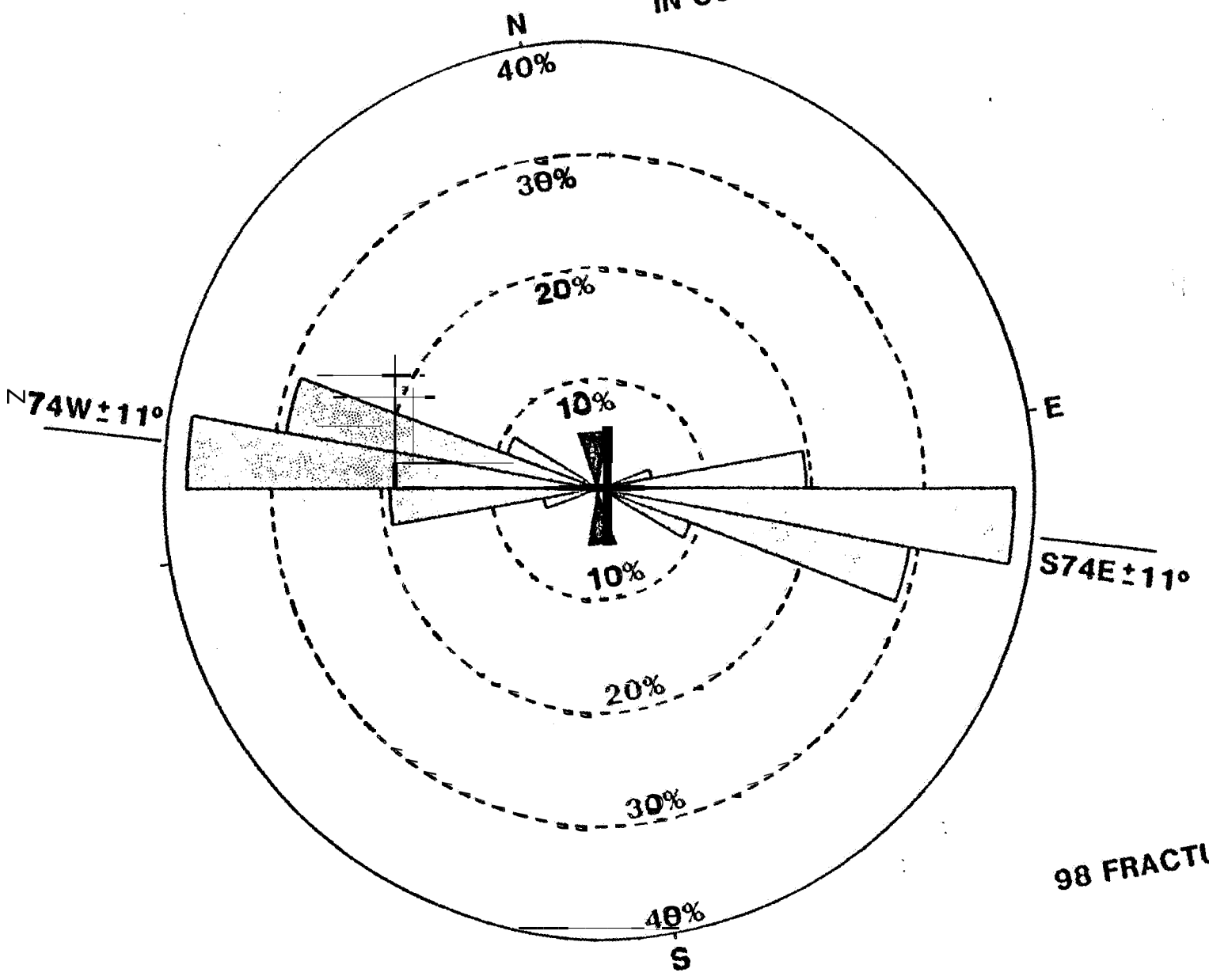
MWX FRACTURE STUDY

I. Empirical approaches
   A. Field mapping (USGS)
   B. MWX Data: core, logs, petrology, rock mechanics
   C. Well tests (CER)

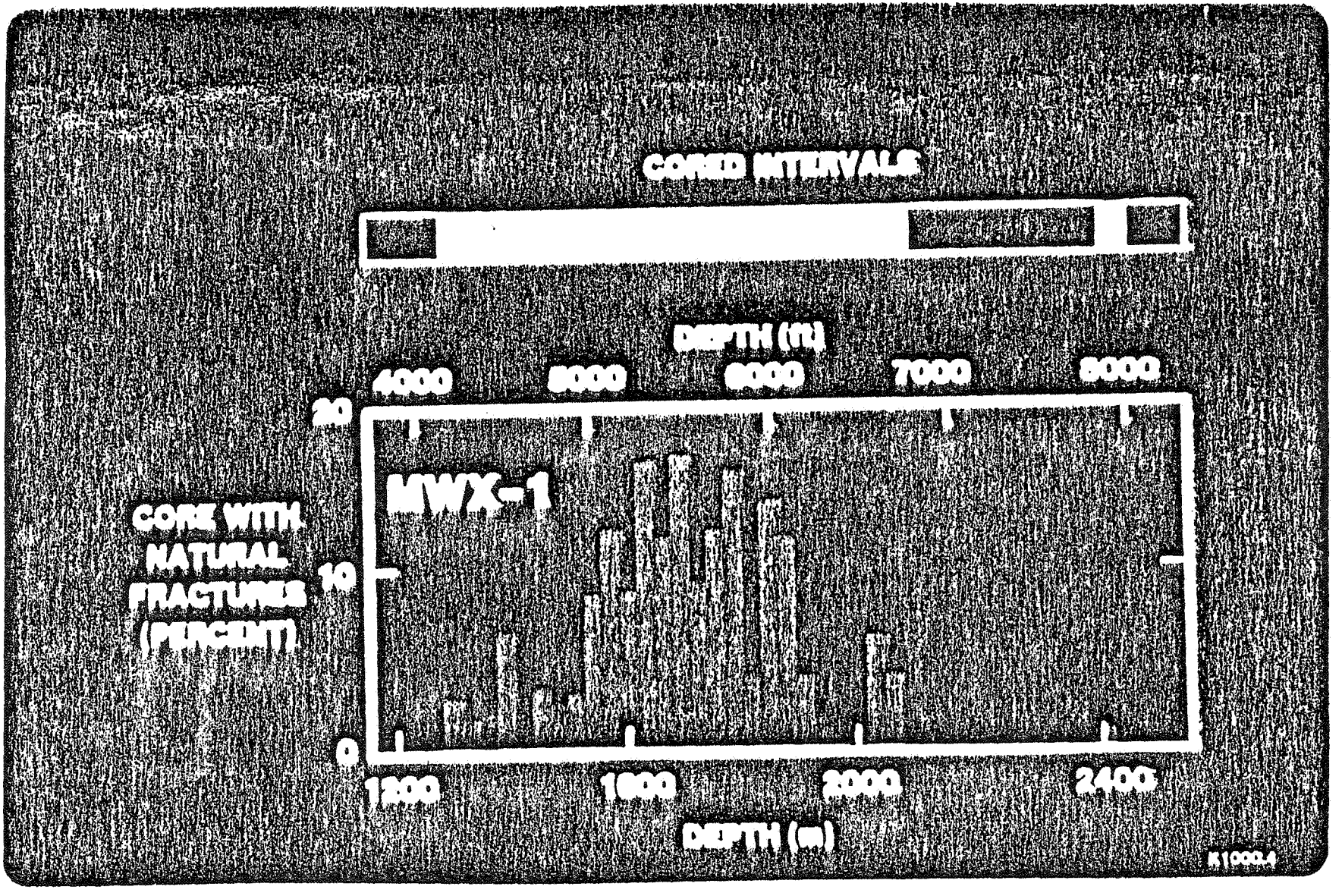
II. Theoretical approaches
   A. Organic maturation (USGS)
   B. Topography (Sandia)
   C. Tectonics (USGS, Sandia)
   D. Overburden (Sandia)

III. Integration of data
   A." ModeUngofFractures (Sandia)
   B. Application of models to reservoir (CER, Sandia)
   C. Well tests and stimulation

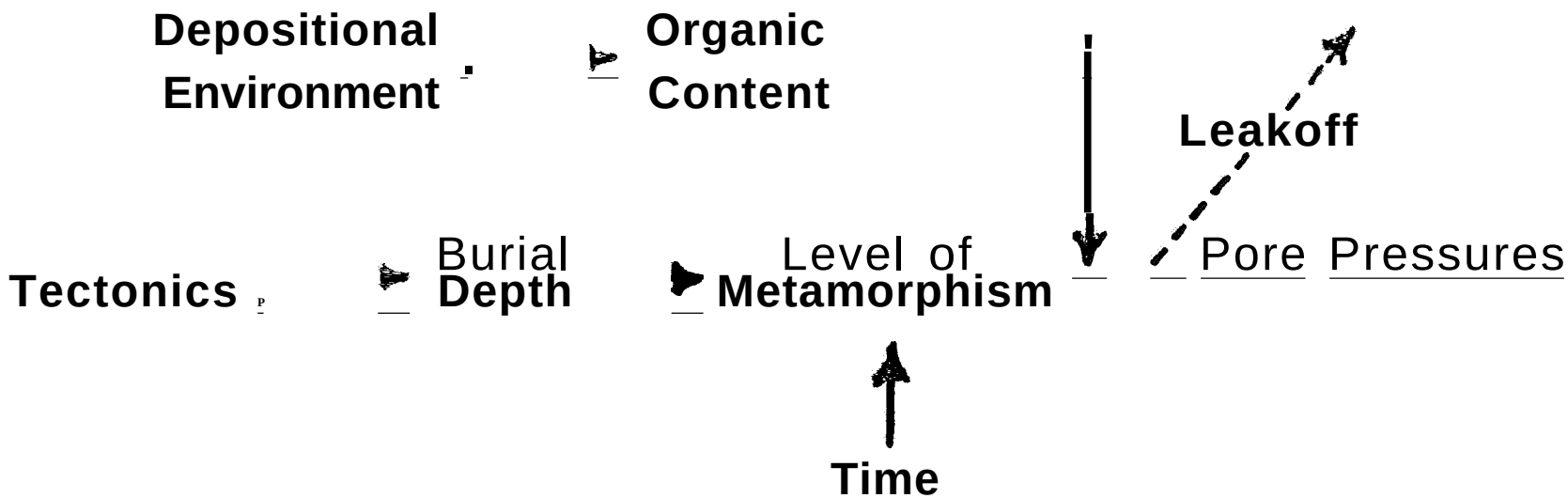
AZIMUTH OF EXTENSION FRACTURES
IN CORE FROM MWX-1, 2, & 3 WELLS



98 FRACTURES


CORED INTERVALS
DEPTH (ft)
4000
5000
6000
7000
8000
20
10
0
MWX-1
CORE WITH NATURAL FRACTURES (PERCENT)
1200
1600
2000
2400
DEPTH (m)
R1000.4

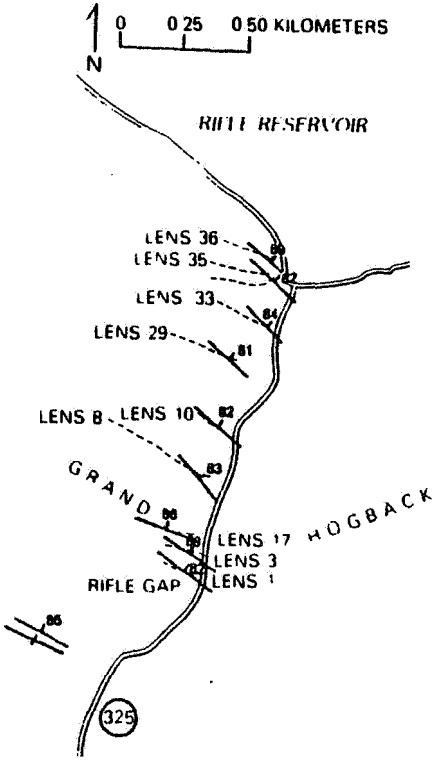
Pore Pore Pressures Affect Fracture Strength of Rocks

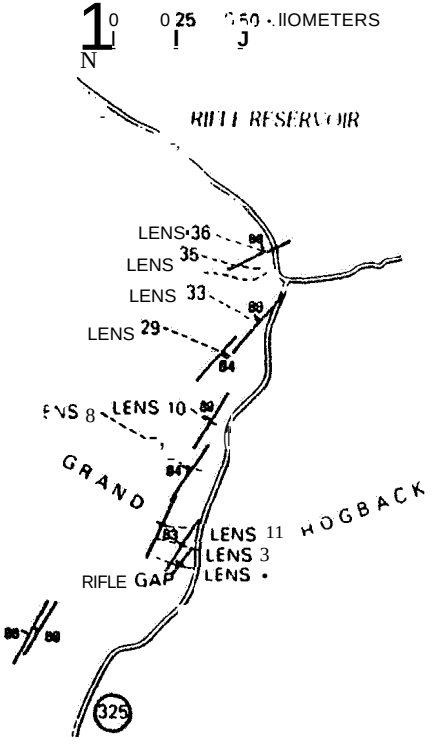


Laboratory Analyses: Total Organic Carbon

Rock -Eval Pyrolysis

Fracture Orientations in Outcrops at Rifle Gap
(Verbeek and Grout, 1984)





Fracture Orientations Across the Northern Piceance Creek Basin (Verbeek and Grout, 1983)

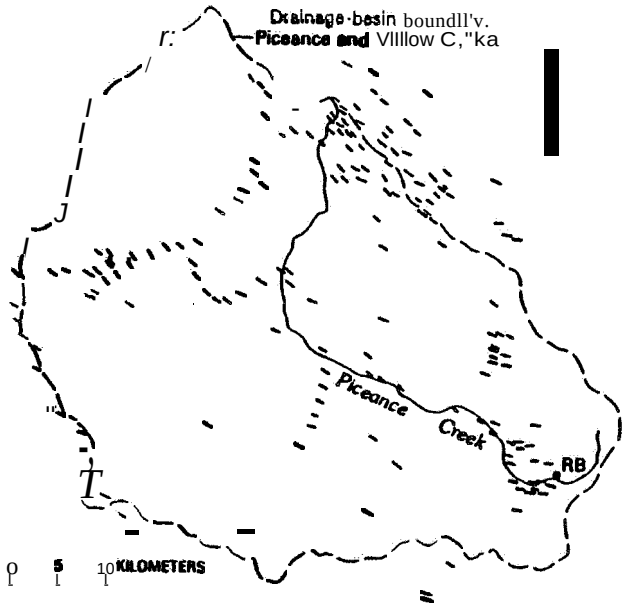
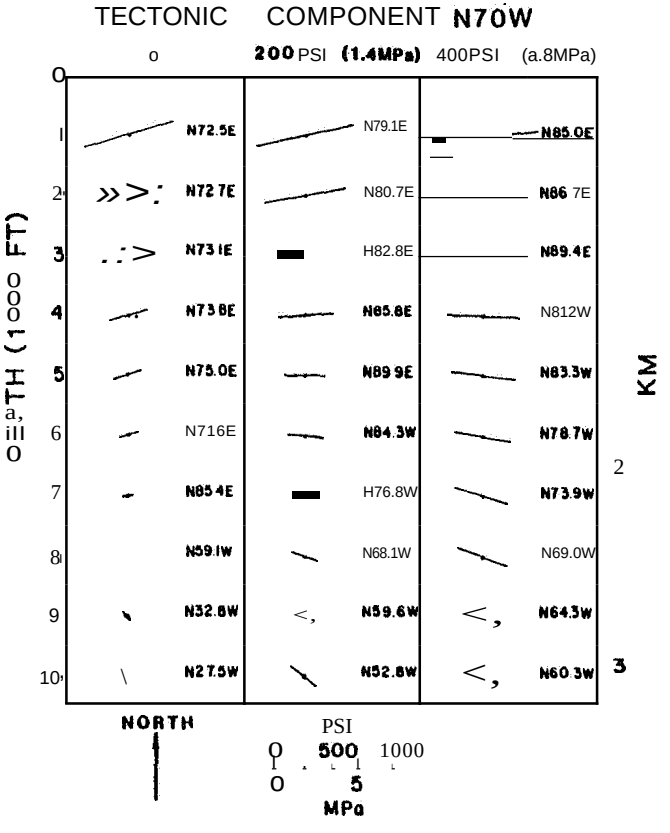
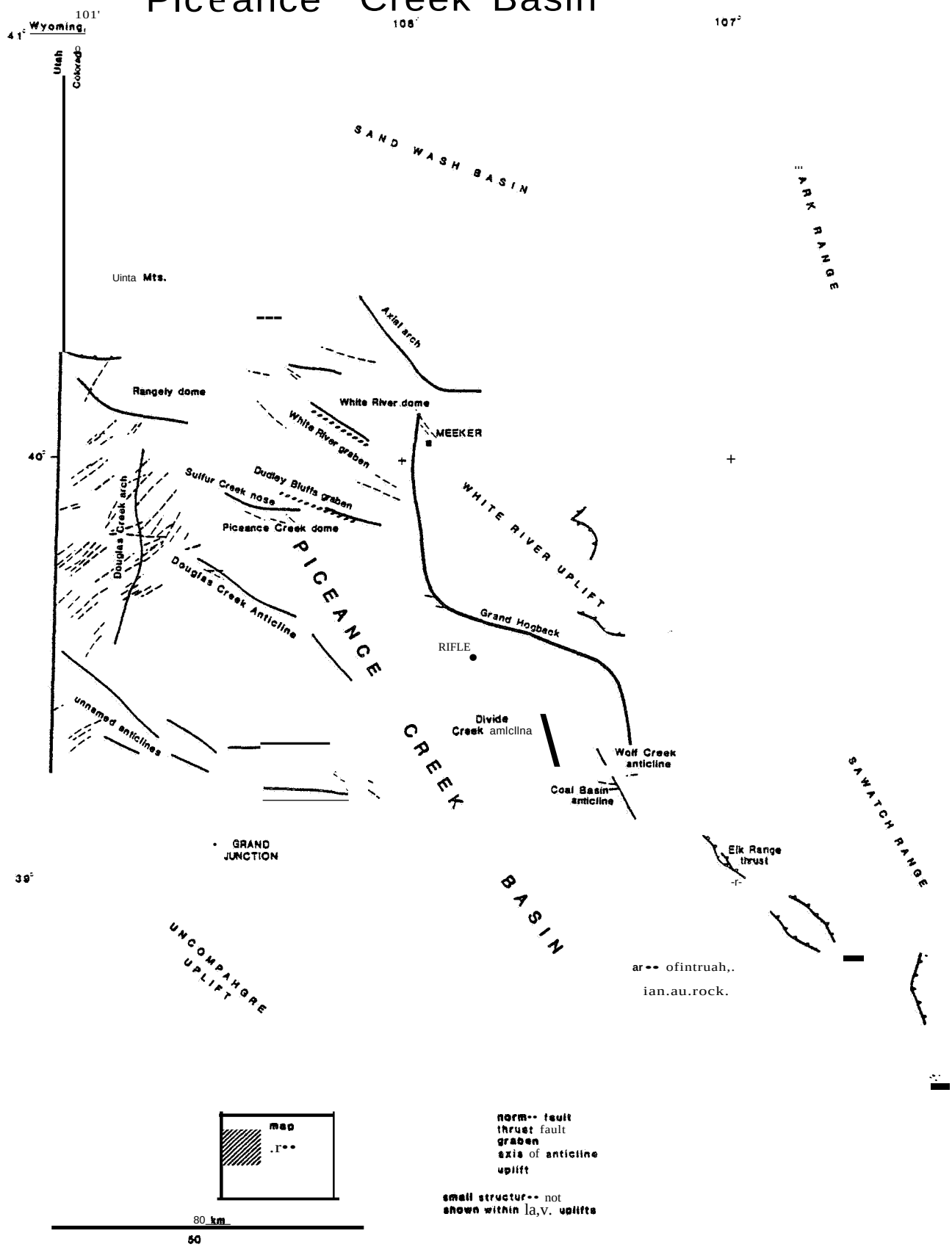


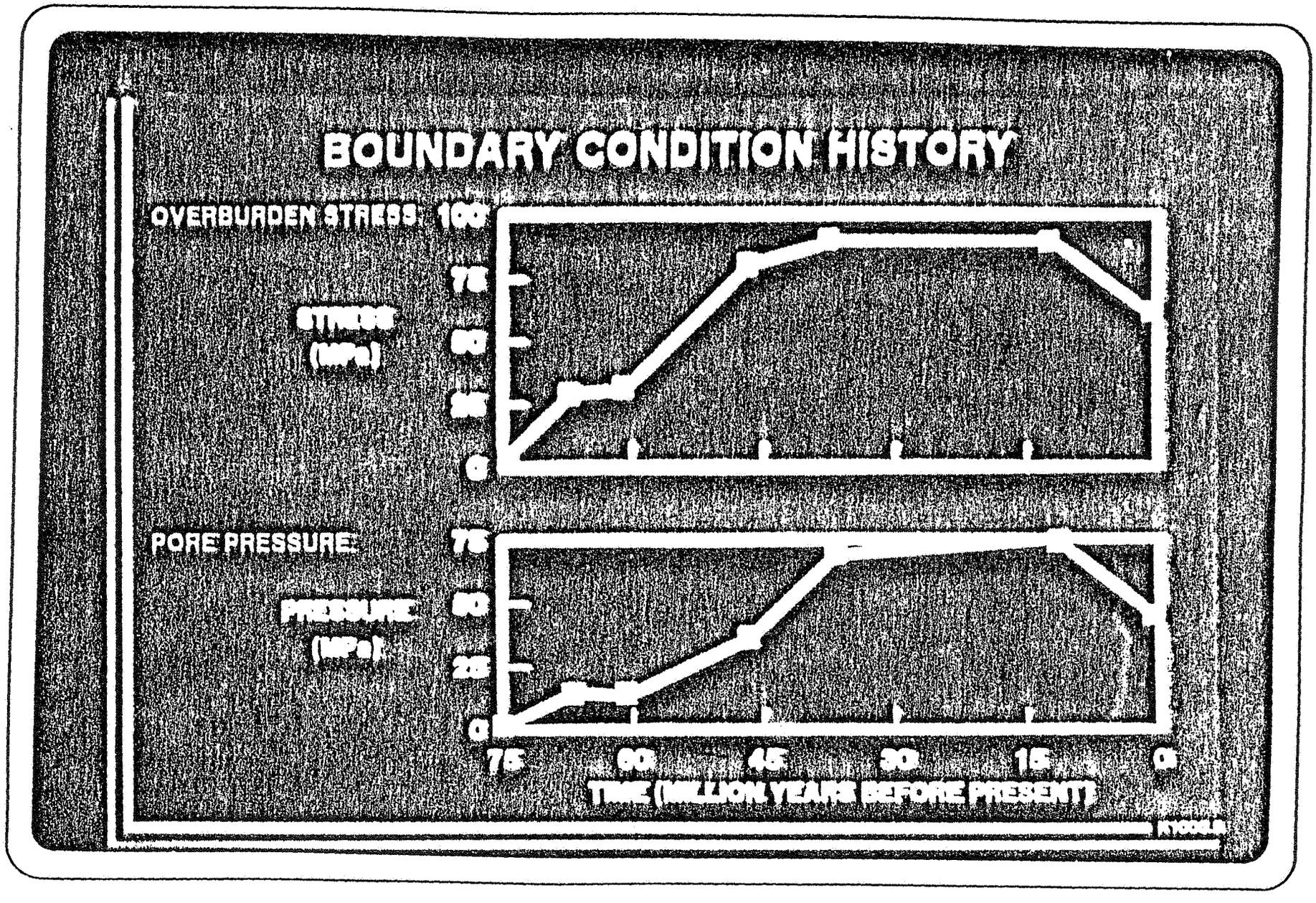
Figure 9—Regional curvature of strike of f_{2C} joint set in Green River and Uinta Formations within the northern. Piceance Creek basin. RB. town of Rio Blanco.

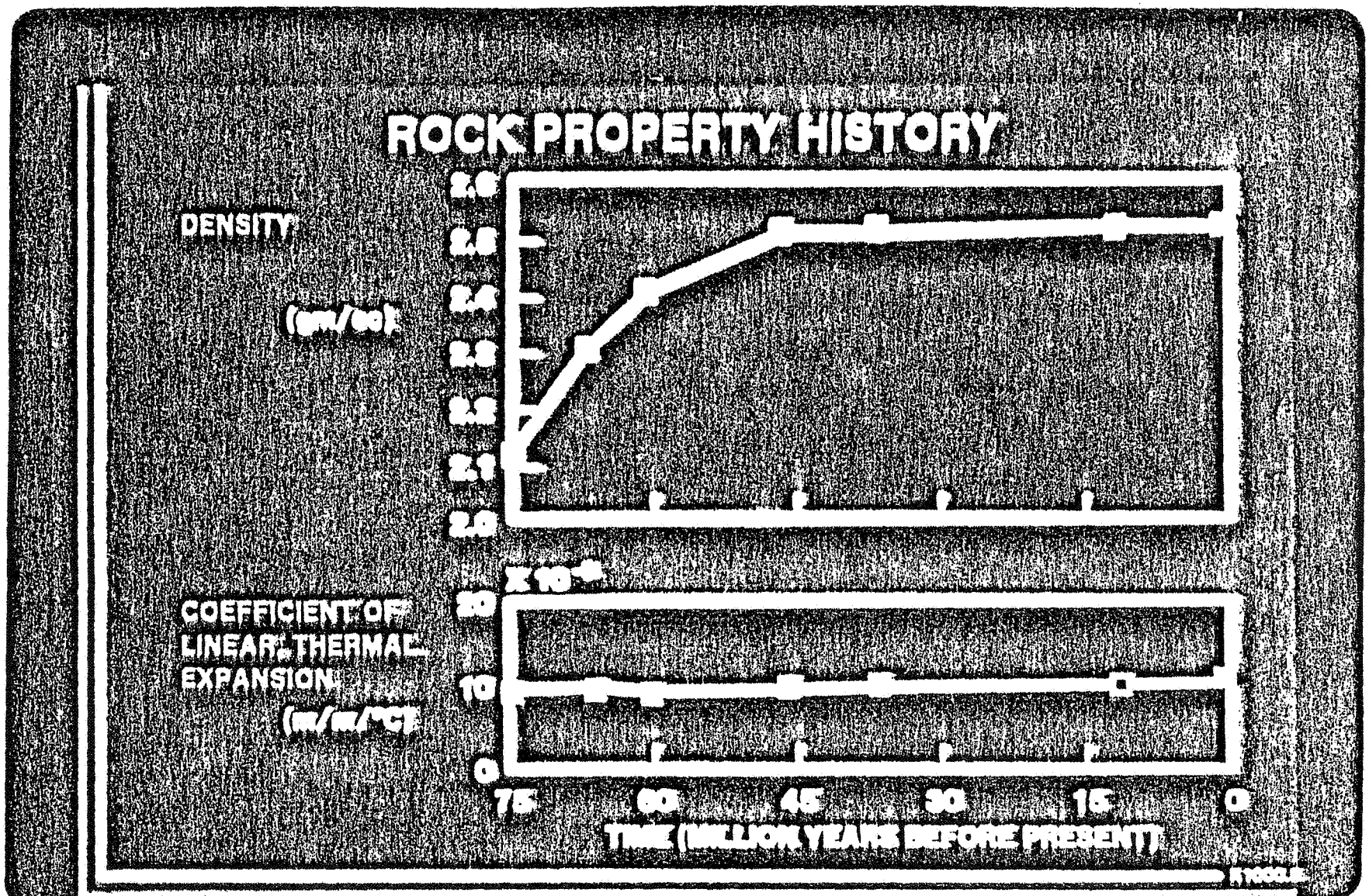
Topographic Induced Variation in Maximum Horizontal Stress at MWX (Clark, 1983)



Struetural Products of Tectonic Stresses in the Plceance Creek Basin




BOUNDARY CONDITION HISTORY
OVERBURDEN STRESS:
STRESS (MPa)
100
75
50
25
0
PORE PRESSURE:
PRESSURE (MPa)
75
50
25
0
75
60
45
30
15
0
TIME (MILLION YEARS BEFORE PRESENT)


ROCK PROPERTY HISTORY
DENSITY
COEFFICIENT OF LINEAR THERMAL EXPANSION
10
0
75
60
45
30
15
0
TIME (MILLION YEARS BEFORE PRESENT)

MODEL OF STRESS HISTORY

- THE MAXIMUM AND MINIMUM HORIZONTAL STRESSES CAN BE INFERRED FROM AN ELASTIC MODEL WITH APPROPRIATE:
- ELASTIC PROPERTIES (EITHER CONSTANT OR TIME VARYING)
  - YOUNG'S MODULUS
  - POISSON'S RATIO
  - DENSITY
  - COEFFICIENT OF LINEAR THERMAL EXPANSION
- ASSUMED BOUNDARY CONDITIONS (TIME VARYING AND CUMULATIVE)
  - OVERBURDEN STRESS (GRAVITY LOADING)
  - HORIZONTAL TECTONIC STRAINS
  - PORE PRESSURE
  - THERMAL STRAINS

CALCULATED STRESS HISTORY FOR COZZETTE SANDSTONE

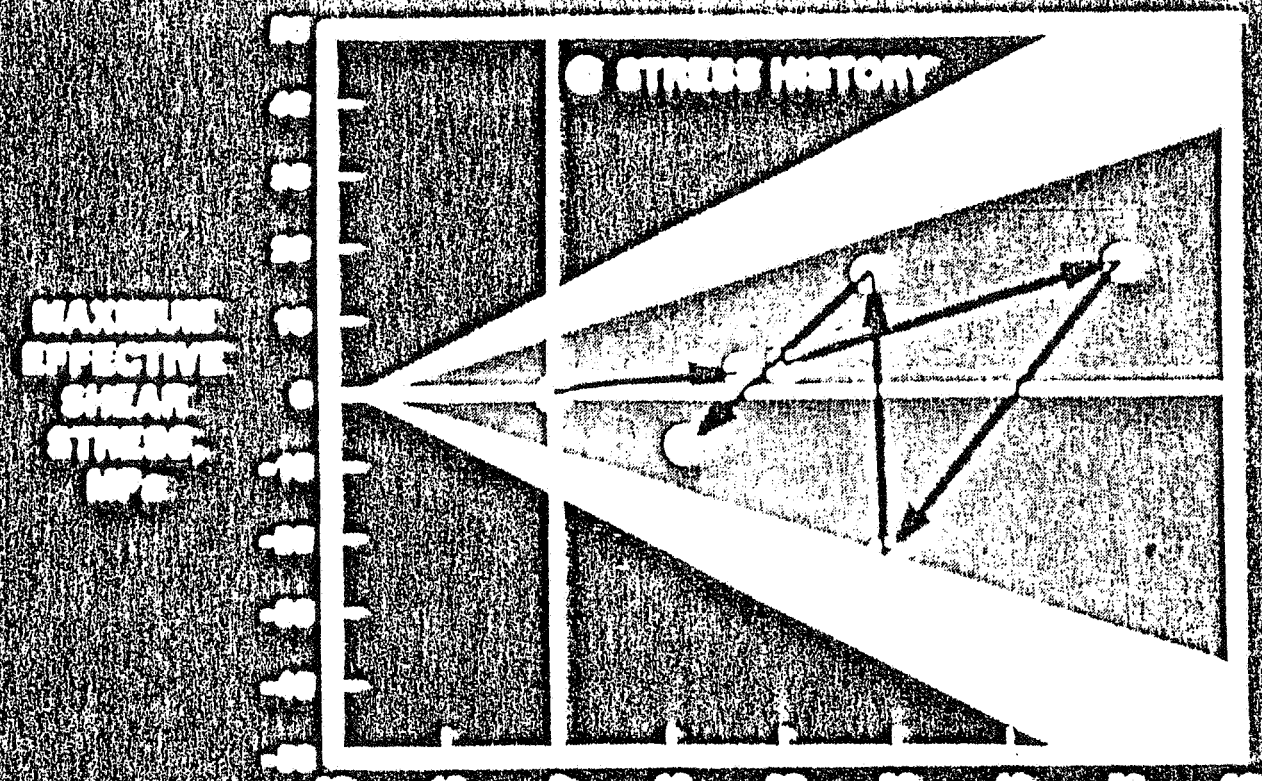


FIGURE 2

PALEO STRESS AND FRACTURE ORIENTATION

	TREND	COMMENT
o HOGBACK SYSTEM OF FRACTURES	N45-60° W	ROTATES WITH DEPTH 0.5% EXTENSION
o FRACTURES IN CORE	N74°W ±llo	
o CALCITE TWINNING	N68-81°W	0.3-0.4% EXTENSION
o TELEVIEWER	WNW	

Fracture Study: Continuing Work

- Refine Fracture Model

  Add visco-elastic calculations

  Mesh with refined empirical observations:

  Calcite twins, tectonics, isotopes, field studies, pore pressures, weH tests

- Calculate Fracture DensitiesIFrequencies

-Measure Laboratory Fracture Permeabilities

- Model Effects of Lithology Changes and Bed Thickness

TITLE:
IMPROVE APPLICATION OF CONVENTIONAL LOGS TO TIGHT SANDS

ORGANIZATION: CER CORPORATION
PRINCIPAL INVEST1GATOR: G.C. KUKAL

PERIOD OF PERFORMANCE:
JANUARY 1, TO DECEMBER 31, 1984

CONTRACT OR PROJECT FUNDING: CONTRACT NO. 37-1075

RESEARCH FUNDING: 115K
MWX SUPPORT FUNDING: 126K
TOTAL: 241K

INTRODUCTION

The Department of Energy (DOE) Western Gas Sands Subprogram (WGSS) has supported log interpretation R & D at CER for six years. The objective of this paper is to prov,ide an account of work performed during 1983-1984.

Two major areas are discussed:

- The status of log interpretation R&D for tight gas sands; and
- CER log interpretation support functions for MWX.

BACKGROUND

The 1977 Western Gas Sands Project(Subprogram) Plan identified several principal activities to comprise the subprogram. These included resource assessment, laboratory R & 0, and field research, development and demonstration. Logging technology development was stressed throughout the plan document as an integral portion of each principal activity.

In November 1980, a WGSS workshop was held to rethink the subprogram direction and objectives. Again logging technology development was identified as a key objective.

GOALS AND OBJECTIVES

The goal of the CER logging R & Deffort is to develop techniques for log analysis which will bring reliability up to confidence levels consistent with the accuracy required to determine reservoir characteristics and for the selection of intervals to be completed and/or stimulated.

Specific tight sand objectives include the following:

- Develop log interpretation methods to accurately characteriz.e lithology, clay volume, clay type, porosity, formation water salinity, gas saturation, matrix permeability, and fracture permeability.
- Develop and fully utilize a MWX depth correlated log and core data base. Provide the data base to all project participants that require thisdata.
- Develop analysis techniques specific to requirements dictated by MWX well conditions eg., oil base mud (MWX 1 and 2), high barite content (MWX 1,2 and 3) and high mud filtrate salinity (MWX 3).
- Support MWX operations with timely interval and zonal log analysis reports which utilize new techniques developed for low permeability reservoirs.
- Support MWX completion activities, eg., perforation interval selection, cement evaluation, stress barrier interpretation and regional azimuthal stress analysis.

NEW LOG INTERPRETATION TECHNIQUES

Many new analytical procedures are outlined in the two enclosed technical papers. Because these papers outline the technology in detail, this discussion will be confined to merely a listing of the new techniques developed.

The work performed includes the development of individual techniques designed to solve specific problems and the integration of the techniques into a feasible and reliable analytical system. Table I lists the task areas and provides a status of the development and technology transfer of each.

Figure 1-15 are visual output of the miscellaneous techniques discussed in Table I.

MWX PROJECT SUPPORT

Table II summarizes the status ofMWX related log analysis reports. The paludal interval report will. soon be released in its final form. The pral iminary coastal interval report will be available this sUl11I1er. Analysis of the fluvial interval is in progress.

In addition to the MWX interval reservoir characteriz.ation reports, separate reports are being prepared for each interval characterizing the petrophysical relationships.

FUTURE RESEARCH AND DEVELOPMENT

CER, s present work and plans for the foreseeabl e future incl ude the following:

- Detailed log analysis of the three MWX wells. Reports are being provided in a timely manner to support MWX testing and stimulation activities.
- Verification and publication of the log interpretation techniques that have been developed over the last few years. This includes the performance of case studies to test the validity and practical application of the techniques utilized by this log analysiS system.
- Continued development of new techniques. The new approaches to tight gas sands log interpretation "fall out" from detailed MWX log-core-well testing compari sons and crossplcts.

New ideas or techniques in various stages of documentation include:

- the quantification of permeabil ity in tight gas sands and comparison to core data and well tests;
- application of the new log analysis techniques to several well case studies in varied geologic provinces (testing the universal applicability of the system);
- the CER method of R_W interpretation - verification using produced water data;
- the use of dielectric measurements to quantity R_W and cross-correlation of

the results to the above method;

- redefinition of clay and matrix related nomenclature and new analytical techniques to refiTle matrix constants - using mostly MWX l1etrographic data to verify results;
- fracture detection using modeled log responses - comparison of the method to fracture detection logs and core data; and
- geologic studies using computer log models and regional R_w profile mapping.

CONCLUSIONS

CER has performed significant research in tight gas sands log interpretation. 1983-84 has been an important time for the continued development and transfer of this technology.

The MWX wells and DOE WGSS Core Program have provided the key data needed to carry out logging R&D. This data will be fully utilized to verify new logging techniques. CER will also continue to support MWX testing and stimulation activities by providing detailed log analysis of the MWX wells.

Long range CER research goals include extrapolation of the techniques developed for the MWX wells to wells in other geologic provinces to verify the universal applicability of the techniques.

TABLE I

NEW LOG INTERPRETATION TECHNIQUES

TASK AREA	PRINCIPAL PUilPOSE	DEVELOPMENT STATUS	PUBLICATION STATUS
I. Methods Developed Specific To NWX logging Conditions			
A. Use of photoelectric effect measurement in barite weighted mud	lithology, matrix density, porosity	Functional, need to compare to petrographic data	Unpublished, planned SPWLA (1985-86)
B. Thermal Neutron environmental correction for oil base mud	porosity, gas saturation	finished	Unpublished, may publish in log Analyst
C. Dielectric constant borehole corrections	fracture detection	Functional, highly empirical	No plans to publish
II. General Techniques for Tight Gas Sands			
A. Geologic definition for calibrating clay volume in shale	clay volume	Finished, needs additional documentation	SPWLA (1983) SPE (1984) planned SPWLA (1985-86)
Il. Clay volume log analysis equations			
1. ganlna ray	clay volume, gas saturation	Finished	SPWLA (1983). SPE (1984)
2. density - neutron		Finished	SPWlA (1983), SPE (1984)
3. sonic		Functiona1, needs further refinement	SPE (1984) planned SPWLA (1985-86)
C. Systematic methodology to refine formation clay and matrix constants	clay volume, matrix density, porosity, gas saturation, permeability	"ave developed a highly iterative and tedious system. Need to develop a method using artificial intel! igence	SPE (1984) pla nned SPWl A (1985- 86)
D. Technique to determine influence of clay upon resistivity log	water saturation	Functional, not verified	No plans to publish
E. Technique for modeling matrix density from basic well logs	porosity		
1. gallIna ray		Functional	planned SPWLA (1985-86)
2. photoelectric effect-gamma ray		Functional	
3. photoelectric effect		Functional	
4. bulk density		Functional	
5. sonic - density - neutron-ganlna ray		Not developed	

TABLE I (CONTINUED)

IASK,AIIEA	PRINCIPAL PURPOSE	DEVELOPMENT STATUS	PUBLICATION STATUS
F. Variable Inatrix parameter refinement techniques for gigahertz and megahertz frequency electromagnetic logs	R_W' water saturation, fracture detection	Functional	planned SPWLA (1985-86)
G. Improved excavation effect equation for low permeability formations	gas saturation	Functiona1 but need additlona1 refinement	SPE (1981) No inillediate plan to publish mOre recent refinement
II. Equation to calculate gas saturation using basic well log data (independent of resistivity logs)	porosity gas saturation	highly refined	SPE (1981) SPWlA (1983) SPE (1984)
I. Technique to interpret R_W using lnodeled log responses	R_W water saturation	Functional, requires additional verification and documentation	SPWLA (1983) SPE (1984) planned SPWlA (1985-86)
J. Investigation of tight gas sand invasion profiles - synthetic density and neutron logs to visualize degree of invasion	matrix permeability	documented, however should be correlated to core capillary pressure data	SPE 11981) SPWlA (1983)
K. Qualitative permeability index using Δ Sw technique	matrix permeabllity	Functional, has fair verification, needs more documentation	SPWLA (1983) SPE (1984) planned SPWLA or SPE (1985-86)
I. Quantitative permeability equation	matrix permeabi1ity	Functional at MWX, also works in Travis Peak/Hosston Sands, need to apply elsewhere	planned SPWlA or SPE (1985-86)
M. Natural fracture detection through modeling of basic logs	fracture permeabH ity	Appears functional, but not well verified	SPE (1984) planned SPWlA (1986)
N. Improved bad hole logic - technique to recognize erroneous log data	kh, net pay	Functional	No immediate plans to publ tsh

TABLE II

MWX PROJECT SUPPORT

TASK AREA	PRINCIPAL PURPOSE	DEVELOPMENT STATUS	PUBLICATION STATUS
A. I'etrophysical relationships for the Mesaverde Group. MWX site	project support	most crossplots have been generated for marine. paludal and coastal intervals	planned SPE (1985) planned Sandia Contractor Report (1985) ,
8. Corcoran-Cozzette MWX report	project support	complete - could be revised using newer analytical techniques	Sandia Contractor Report (Dec. 1983)
C. Preliminary Paludal Report MWX-I. MWX-2	project support	complete and later revised	CER Report (March 1983)
Il. Paludal Report MWX-I. MWX-2, MWX-3	project support	complete and revision in progress	CER Report (January 1984)
E. Paludal lleport MWX-I. MWX-2. MWX-3 (Final Report)	project supper t	analysis complete	CER Report (July 1984) planned Sandia Contractor Report (1985)
F. Preliminary Costal Report MWX-l. MWX-2. MWX-3	project support	analysis nearly complete	CER Report (August 19811)
G. Other analysis in progress Lower Fluvfa I MWX-l. MWX-2. MWX-3 Upller Fluvial MWX-1, MWX-2. MWX-3	project support	in progress	several reports are III anned

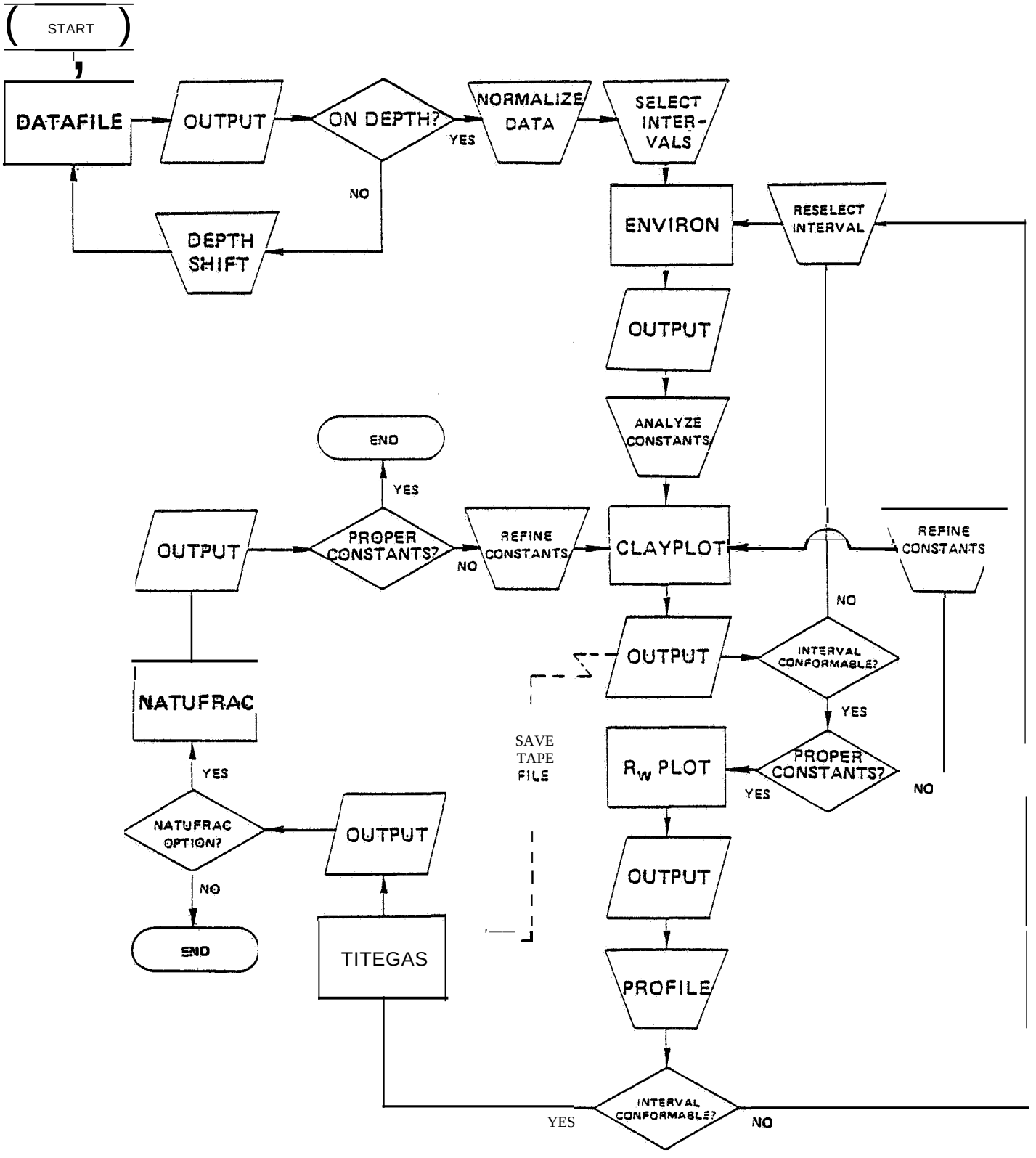


Figure 1. Log interpretation system flowchart

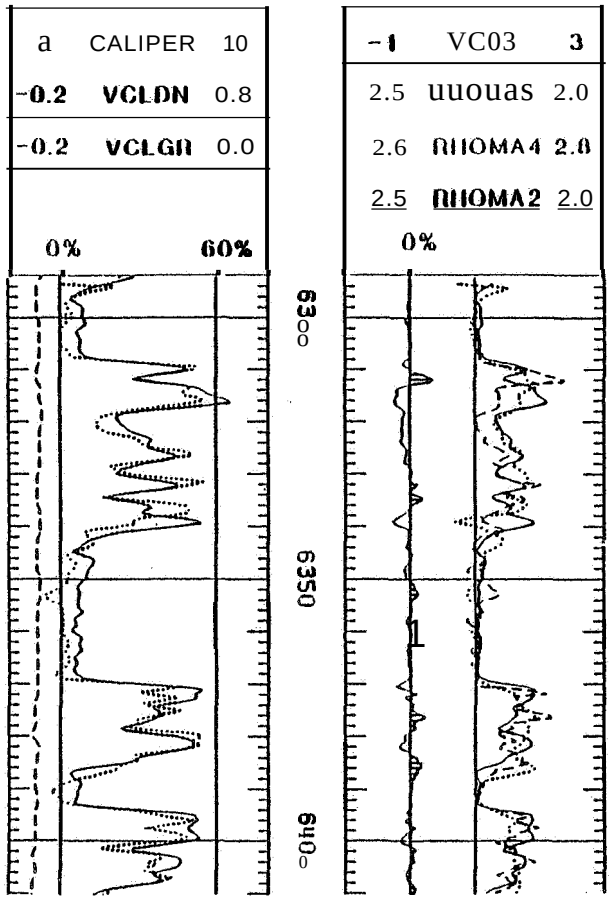


Figure 2. MWX-3 coastal interval matr-Ix analysis

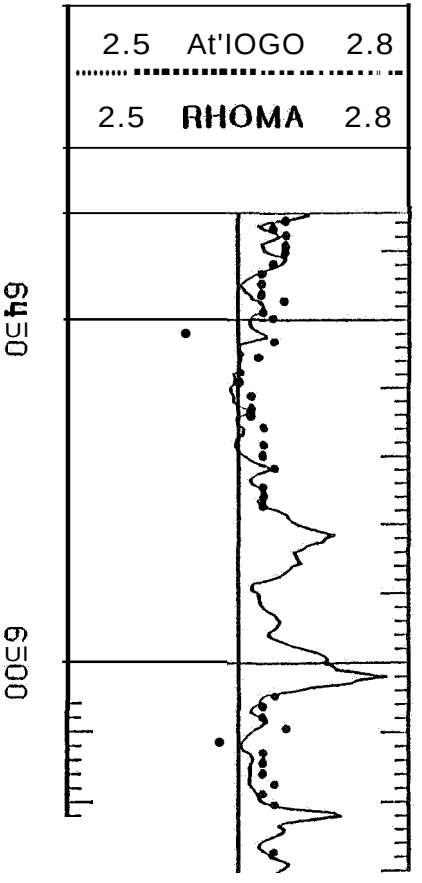


Figure 3, Matrix density compared to grain density, coastal tnterval, MWX-3

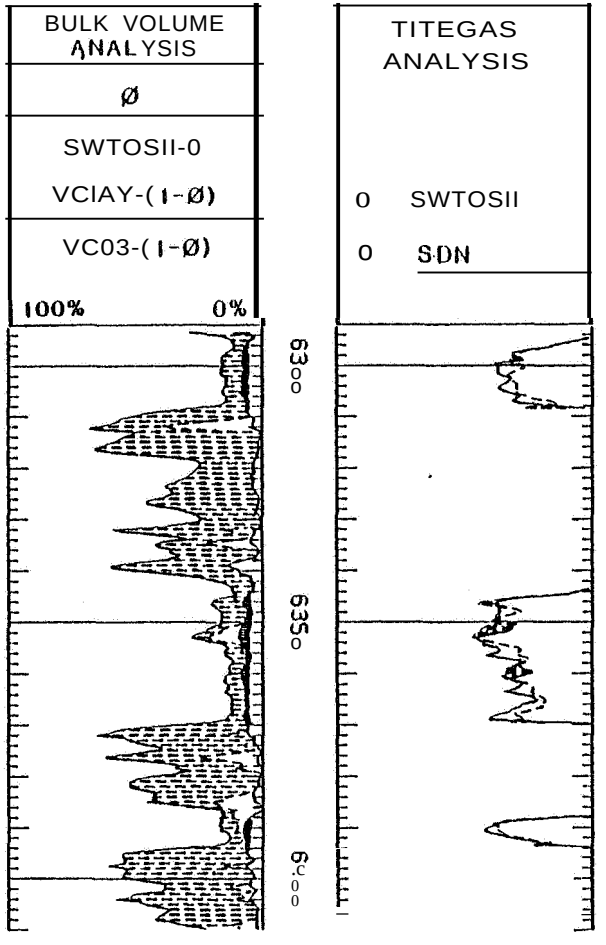


Figure 4_ Bulk volume and saturation analysis for coastal interval. MWX-3

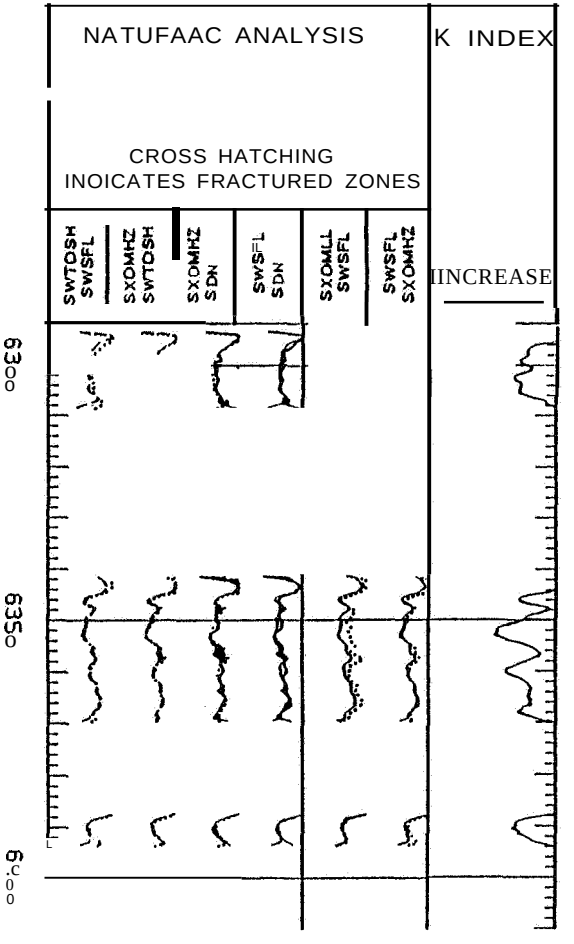


Figure 5_ f'latural fracture analysis for coasta1 interva1. MWX-3

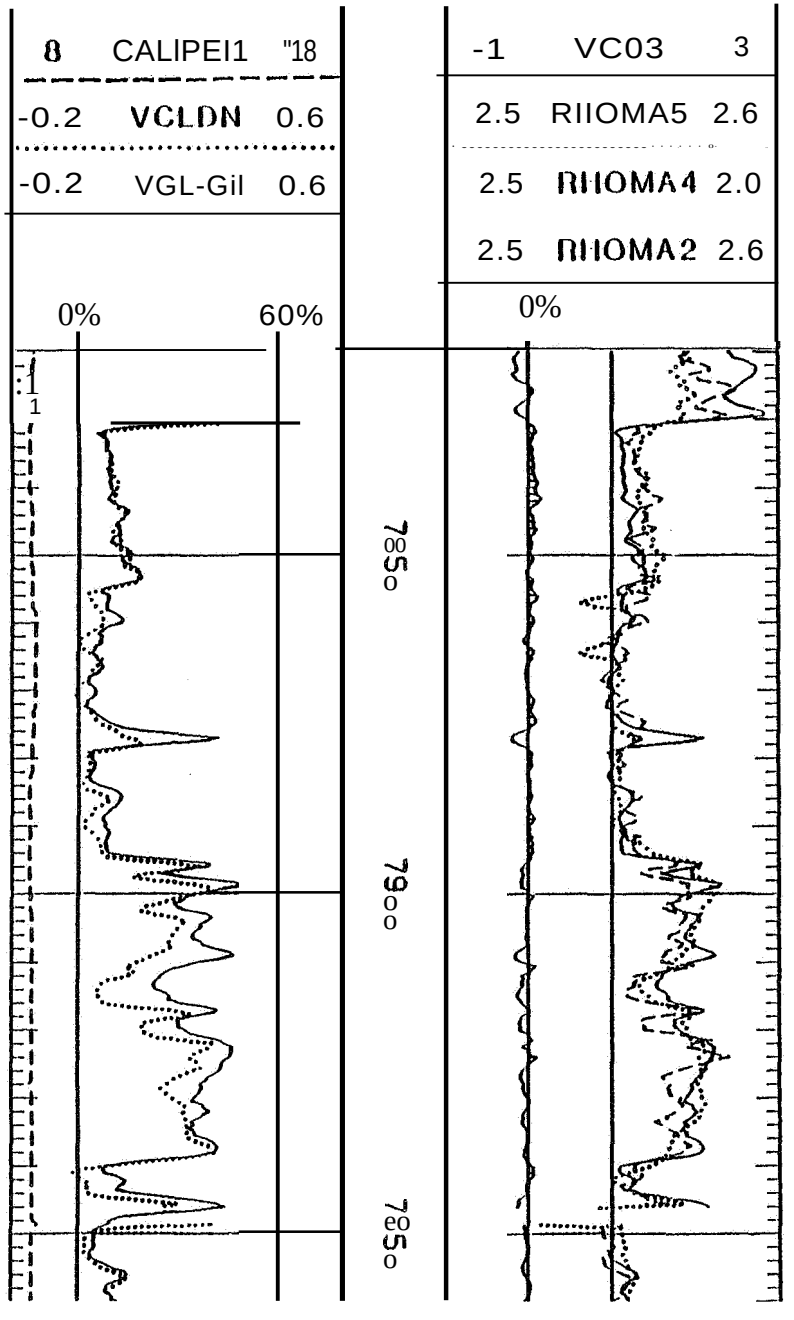


Figure 6. Matrix analysis for Cozzette interval. MWX-1

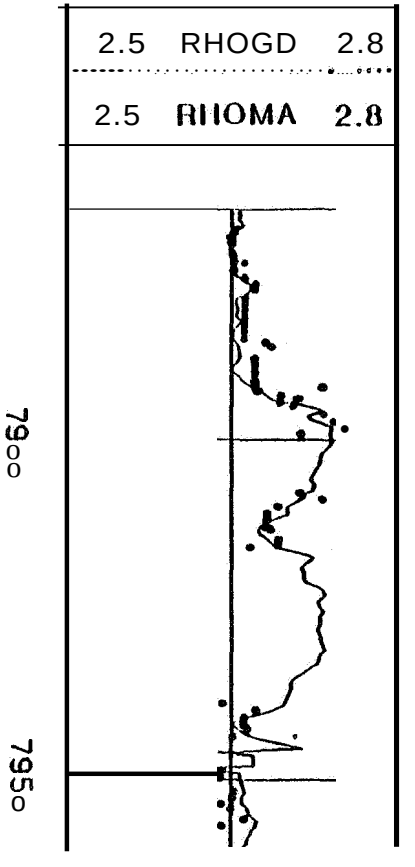


Figure 7. r'1atrix density compared to grain density. Cozzette interval, MWX-1

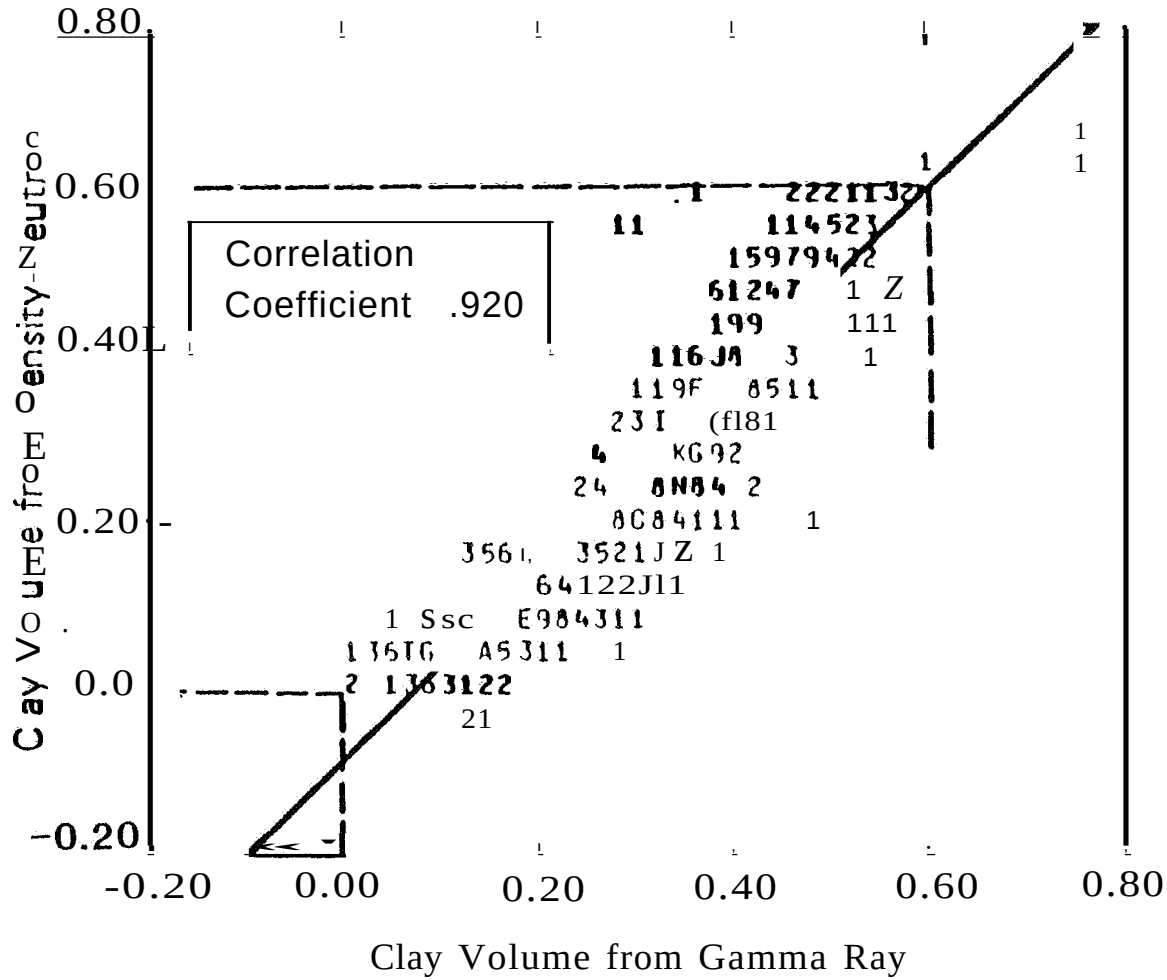


Figure 8. Clay valume analysis for the marine interval. MHX-1

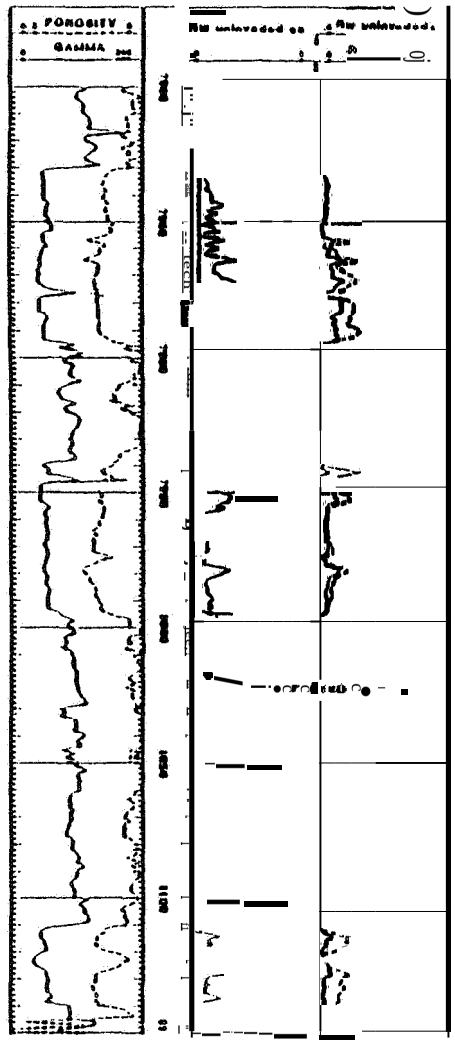


Figure 9 Rw Plot — Raw Calculations, CER MWX-1

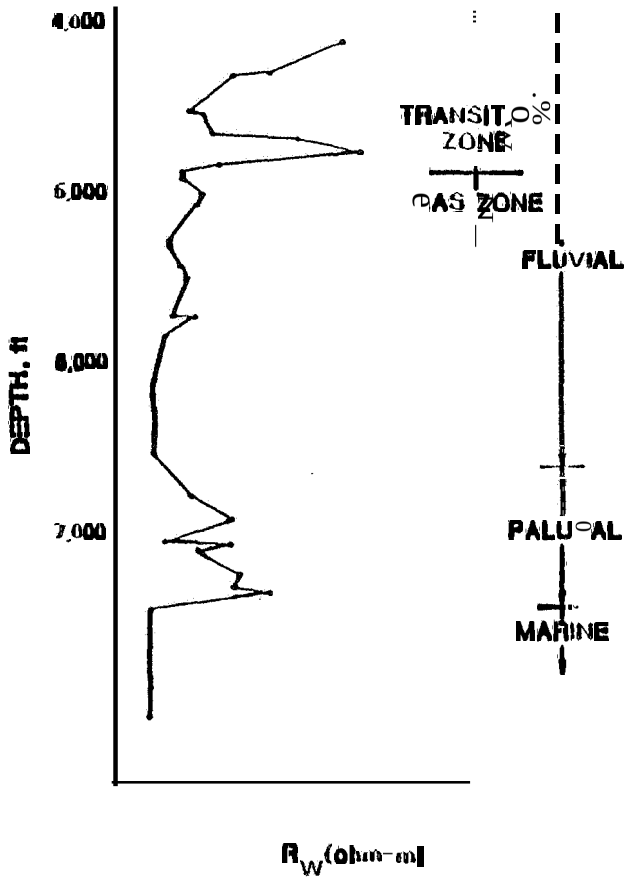


Figure 10 Rw Profile — Interpretation of Rw for Mesaverde Interval, CER MWX-1

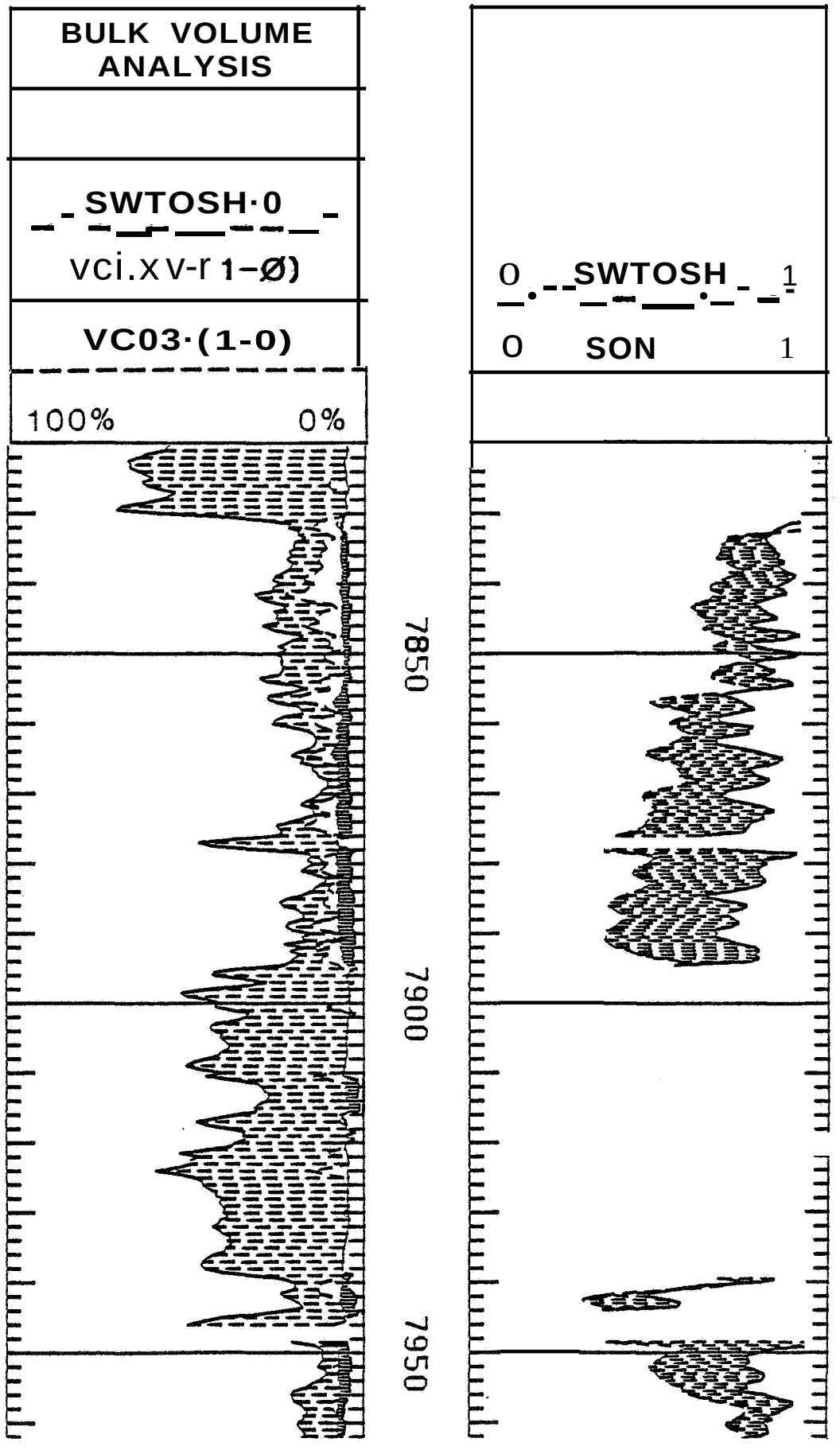


Figure 11. Bulk volume analysis and saturation analysis for Cozzette Sandstone, MHX-1

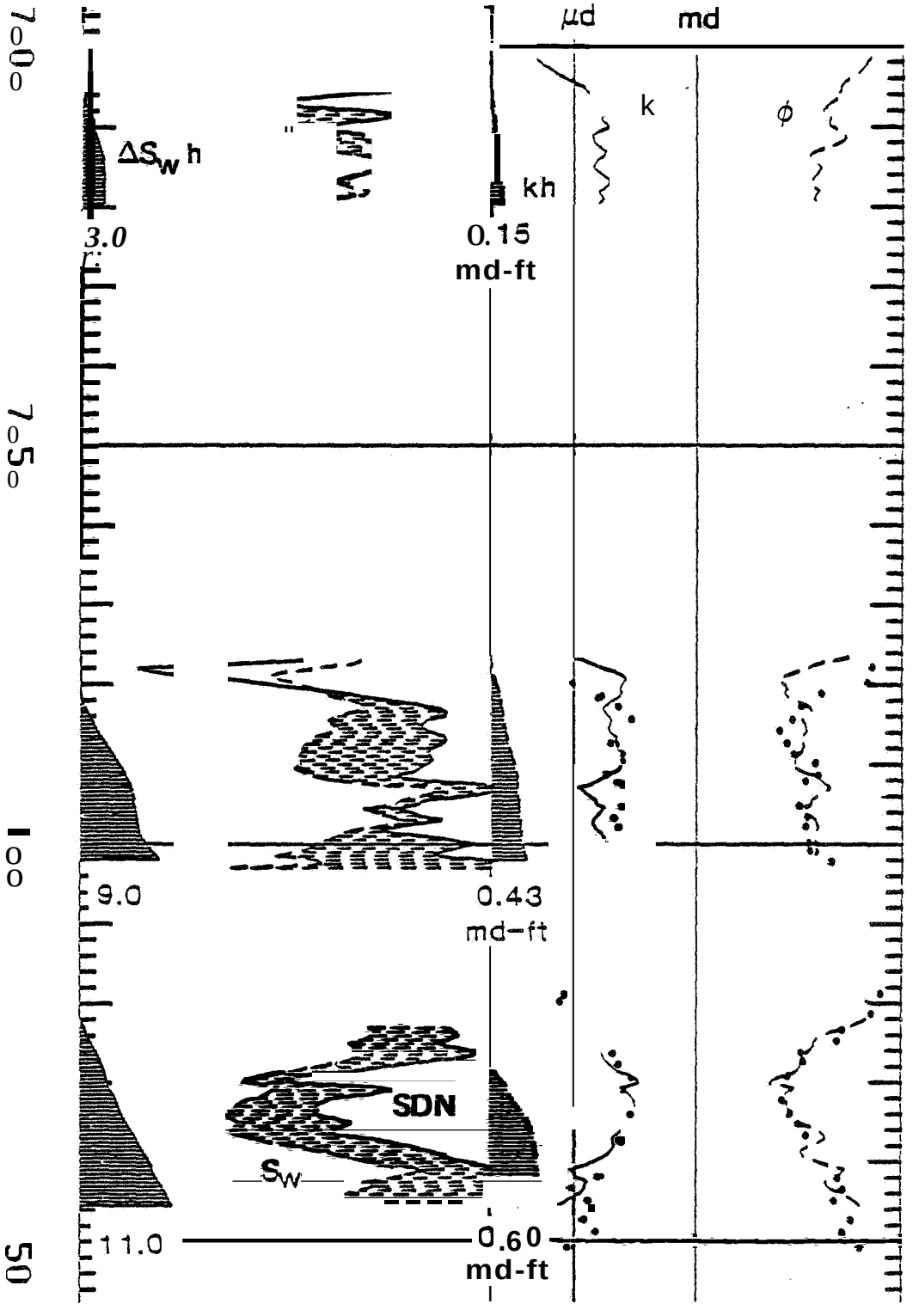


Figure 12. Producibility plot for paludal interval, MWX-3

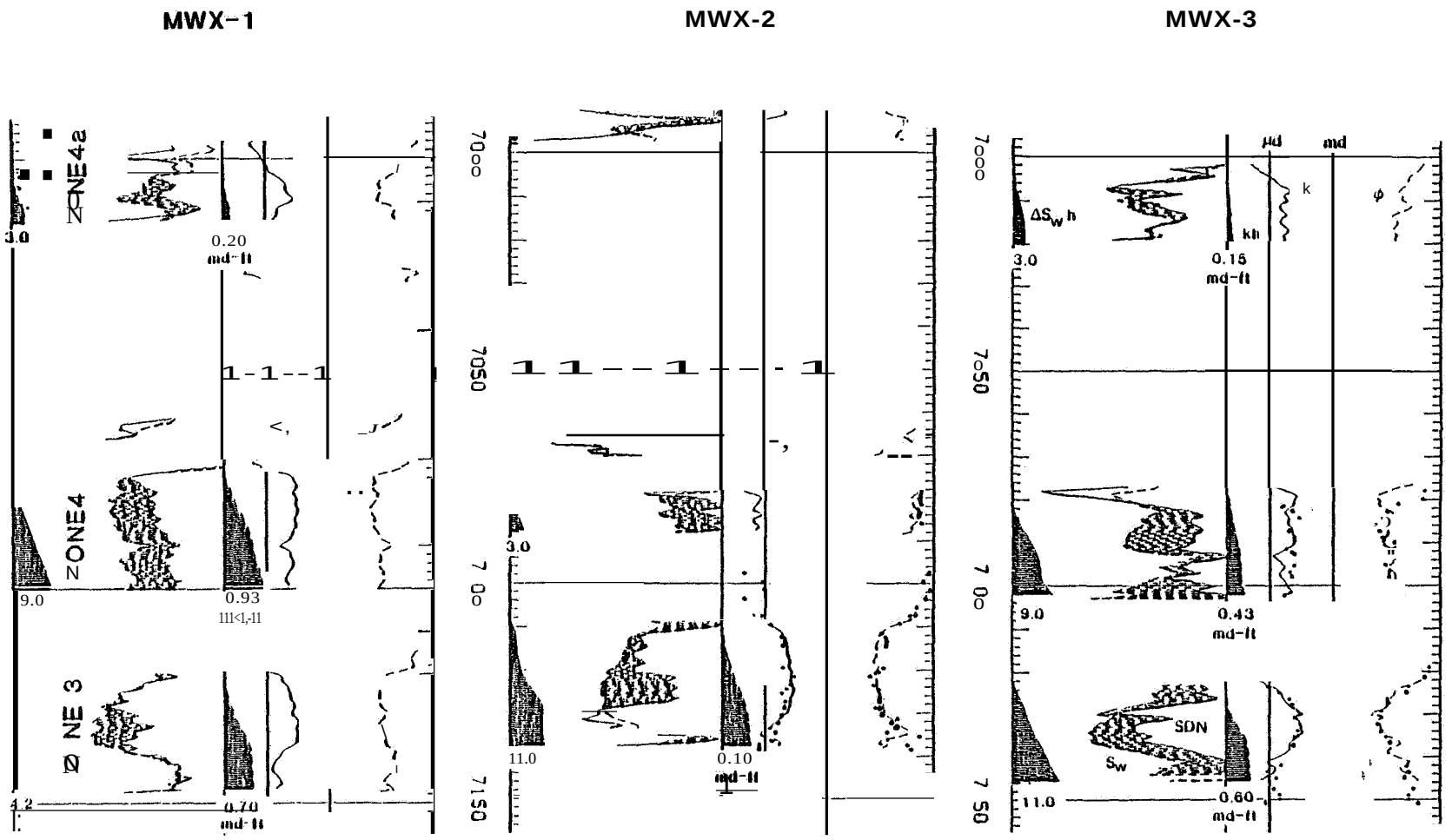


figure 13, Producibil ity plots for zones **3. 4. and 4a MWX paludal interval**

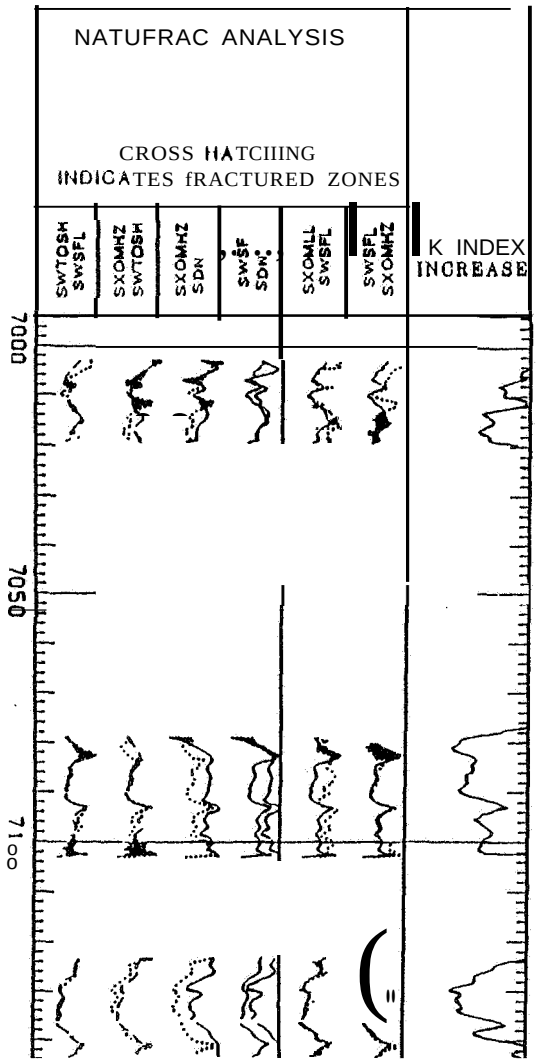


Figure 14. Natural fracture analysis for paludal interval, MWX-3

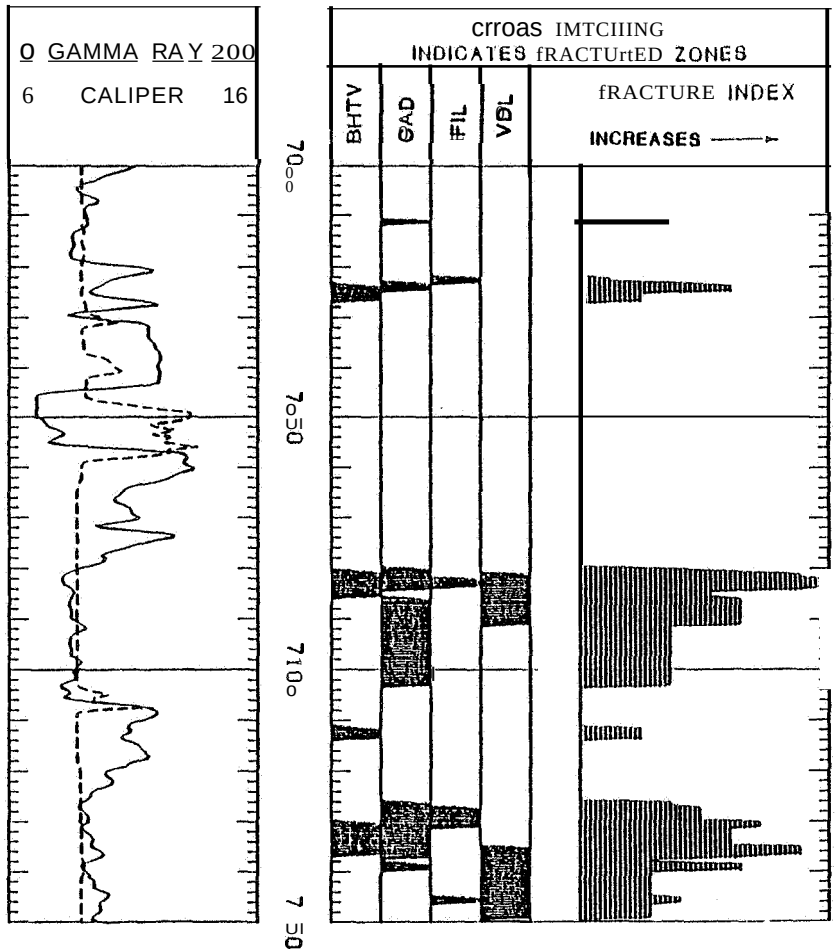


Figure 15. Fracture detection log analysis, paludal interval MWX-3

TIT.LE:
WELL TESTING
RESERVOIREVALUATION

ORGANIZATION: CER CORPORATION'

PRINCIPAL INVESTIGATOR: P. BRANAGAN

PERIOD OF PERFORMANCE:

JANUARY 1, 1984 TO DECEMBER 31, 1984

CONTRACT OR PROJECT FUNDING

37-1075 SANDIA 153k

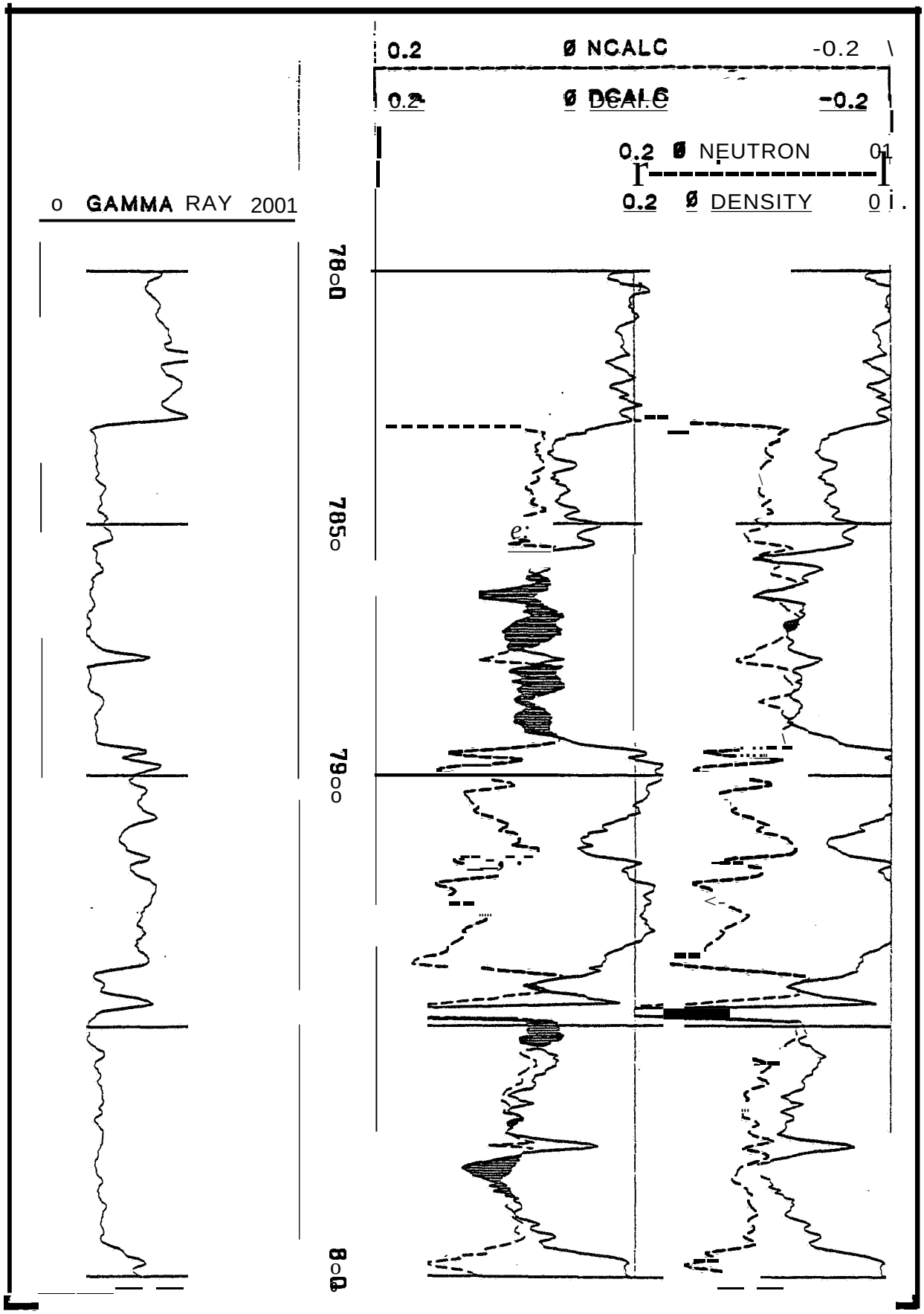
MULTI-WELL EXPERIMENT

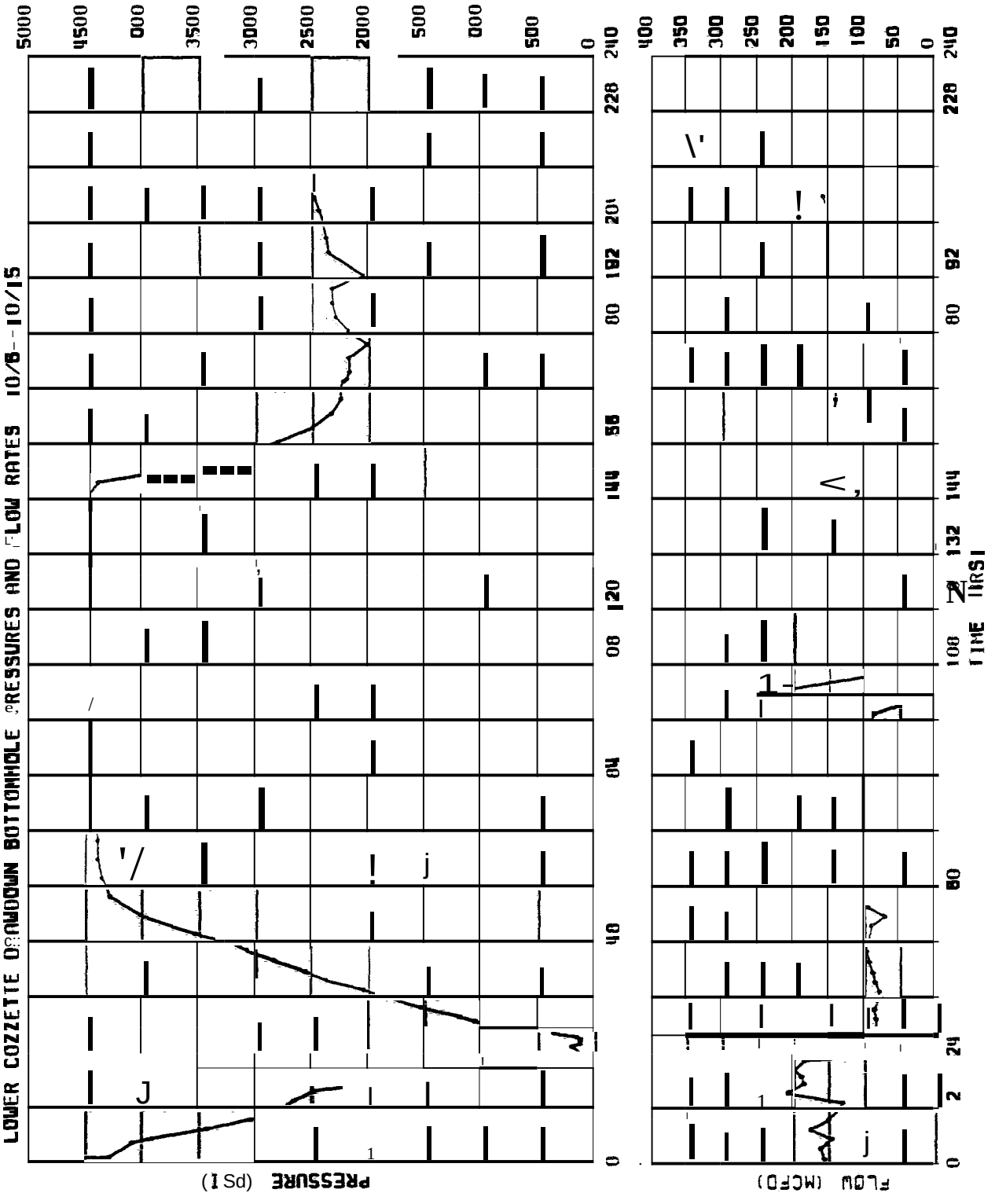
- RESERVOIR MODEL DEVELOPMENT
- TESTING DESIGN
- SINGLE MULTI-WELL TESTING
- ANALYTIC & MODEL SIMULATION OF TEST nESULTS
- STIMULATION CRITERIA & EVALUATION

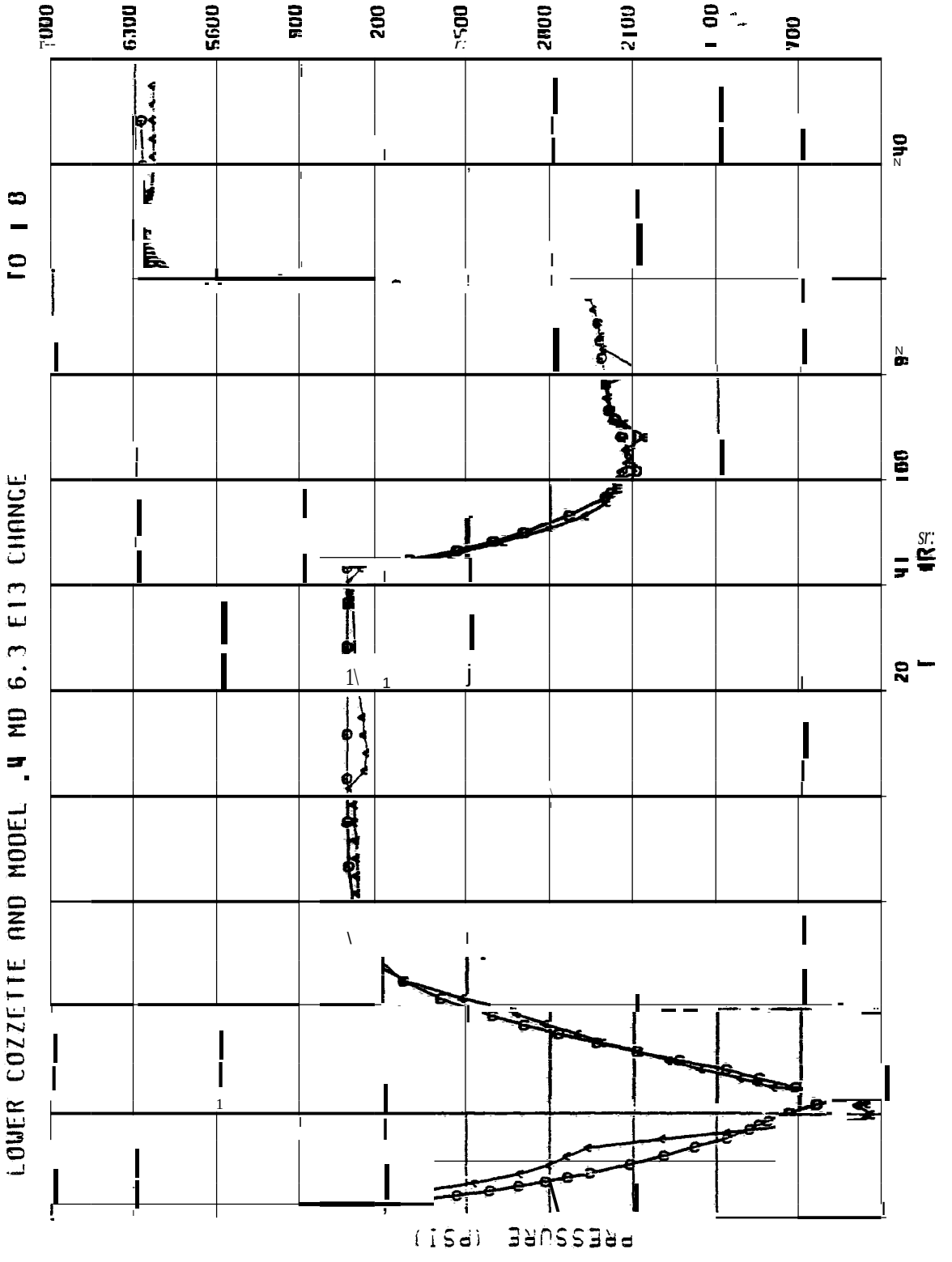
ENT

CER

MWX-1 COZZETTE SANDSTONE




LOWER COZZETTE DRAWDOWN BOTTOMHOLE PRESSURES AND FLOW RATES 10/8--10/15
PRESSURE (PSI)
FLOW (MCFD)
TIME (HRS)

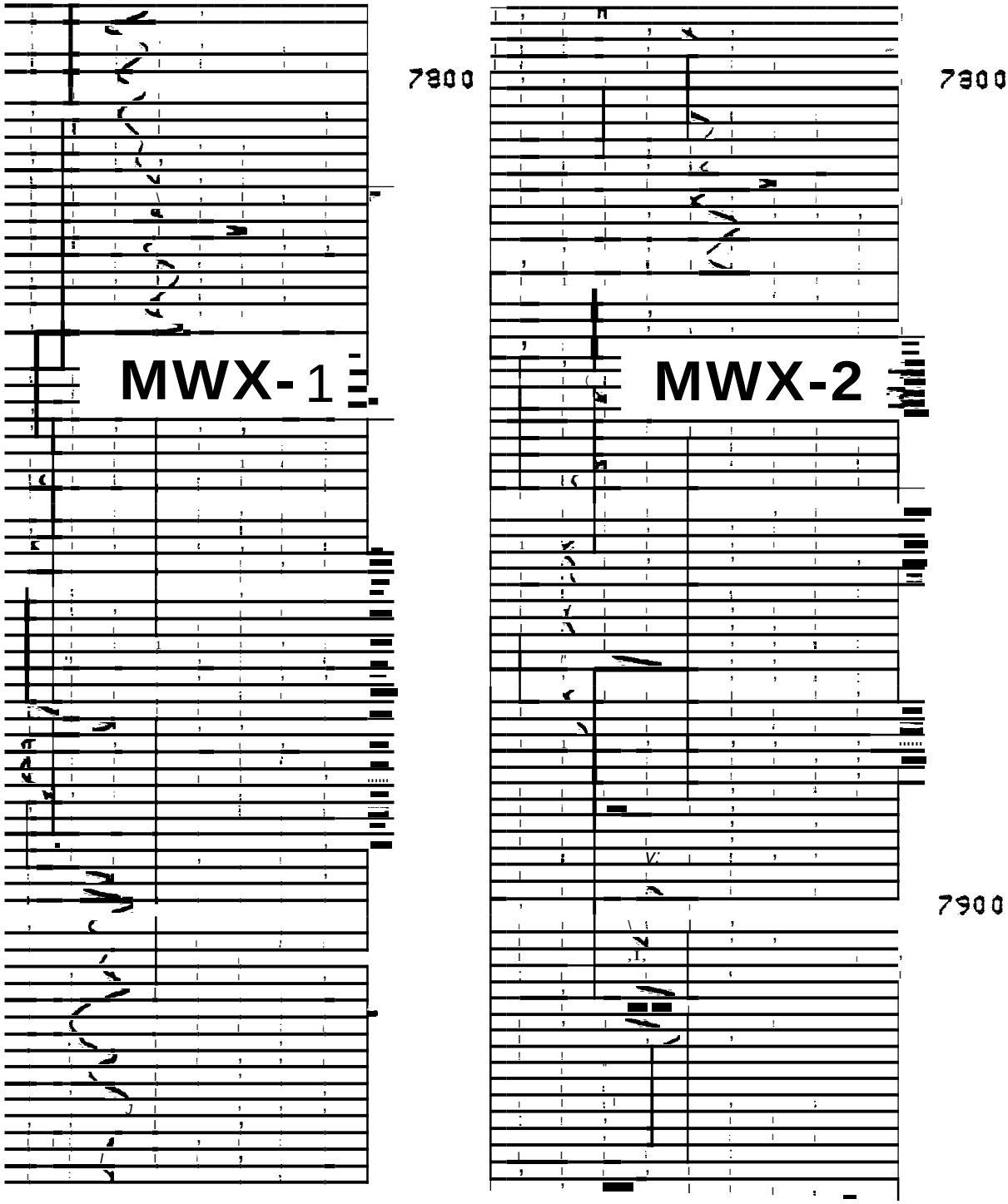

LOWER COZZETTE AND MODEL .4 MD 6.3 E13 CHANGE
PRESSURE (PSI)

SUMMARY
LOWER COZZETTE

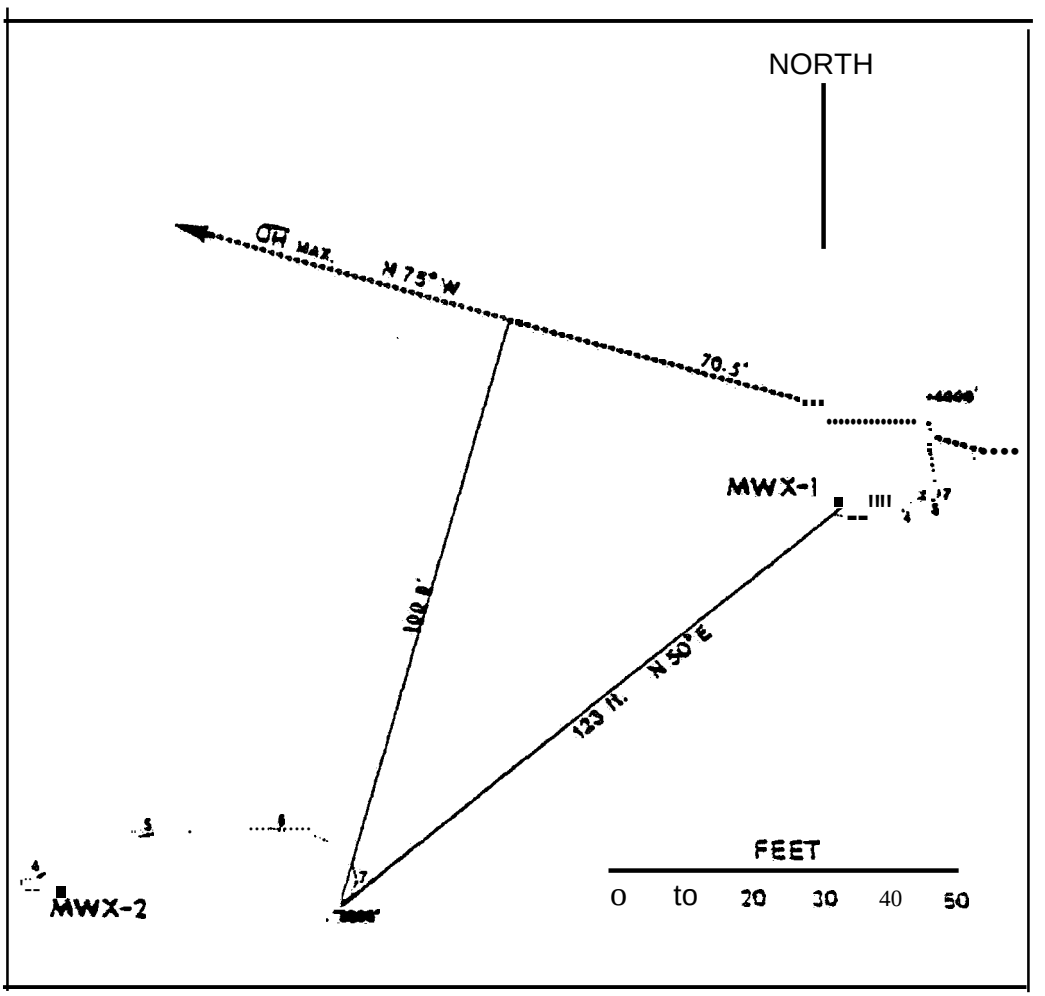
- Core Analysis, k ≃ 1μd
- Initial Buildup, k ≃ 6 to 10pd
- History Match Transient Pressure Test, It ≃ 400μd
- Fracture Gradient 0.86 psi/ft
- High Stress Boundary (1 psi/ft) Between Upper and lower Cozzette < 20 ft
- High Probability of Penetration During Fracture

CER

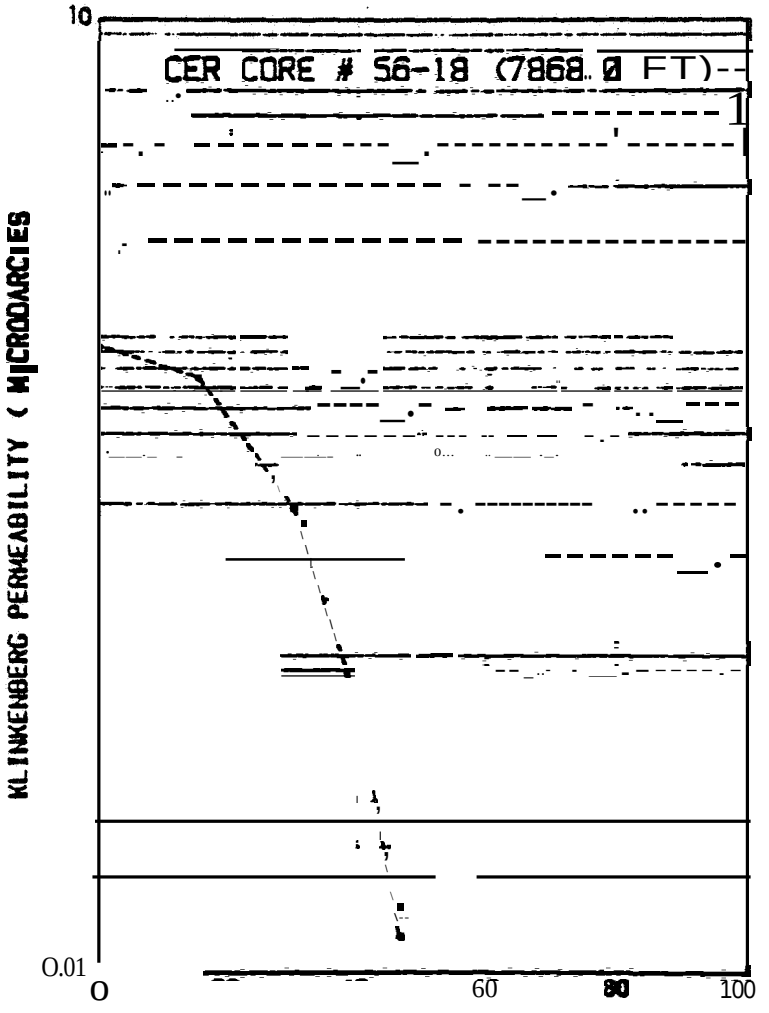
CER



Upper Cozette

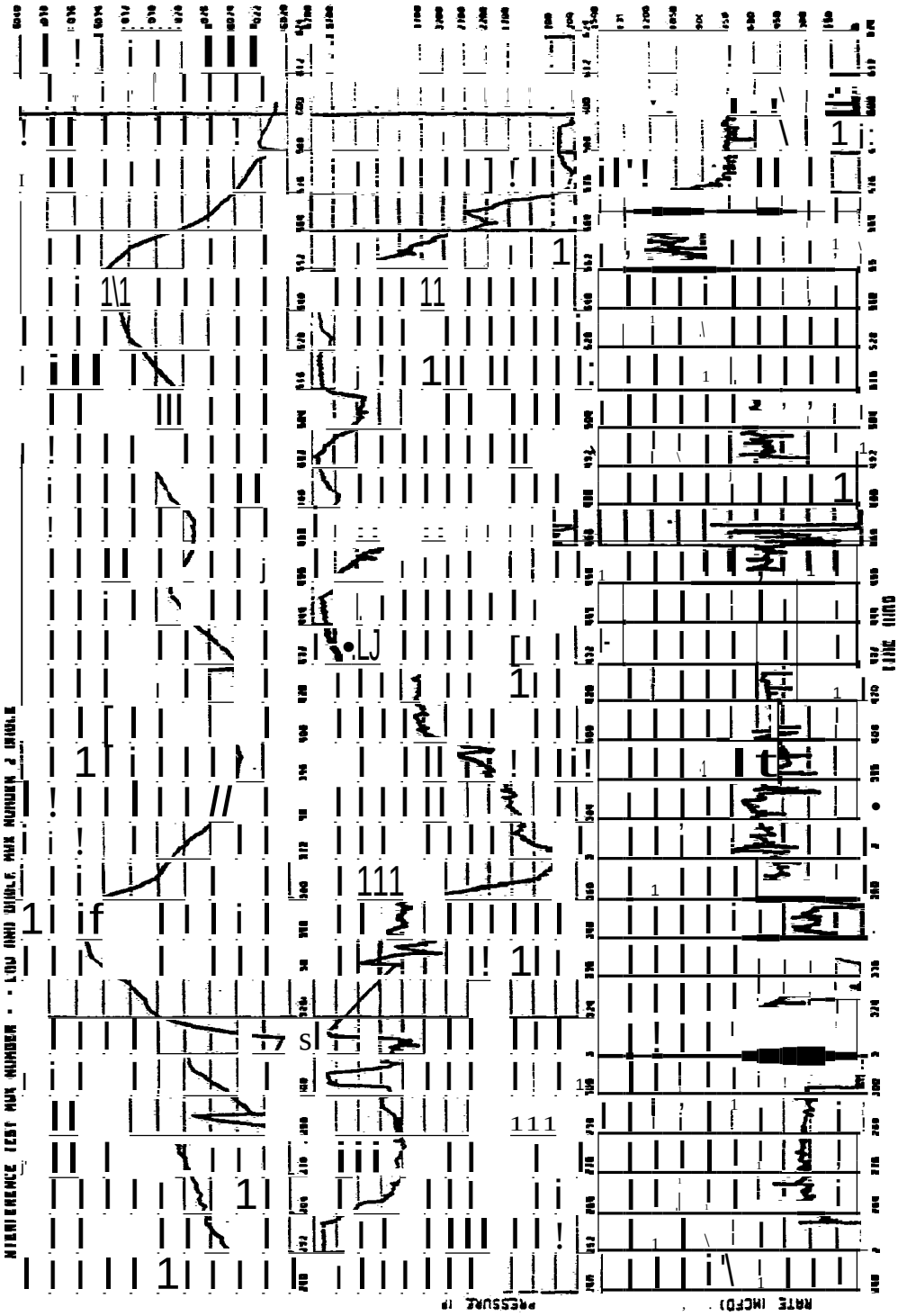


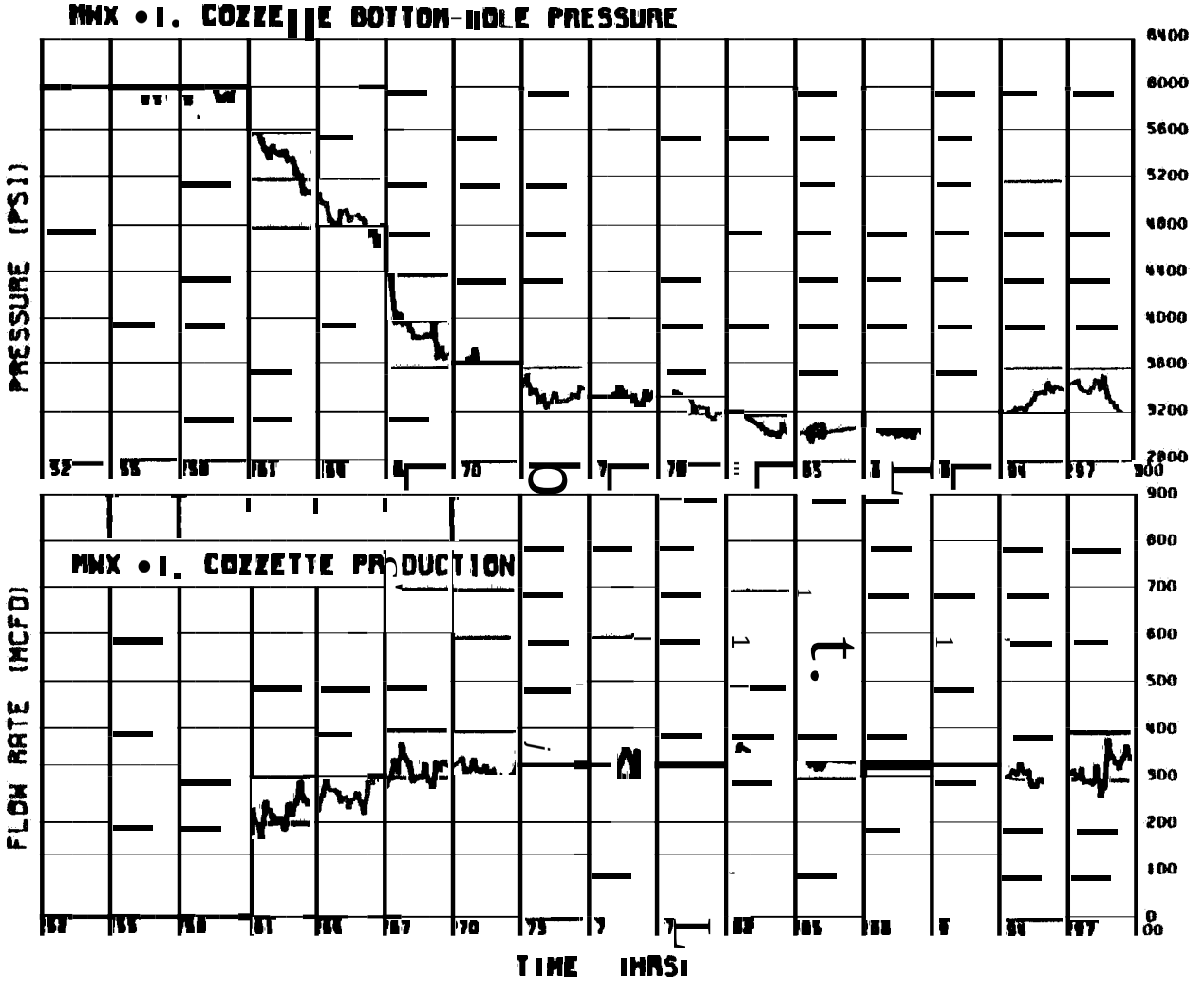
Upper Cazette

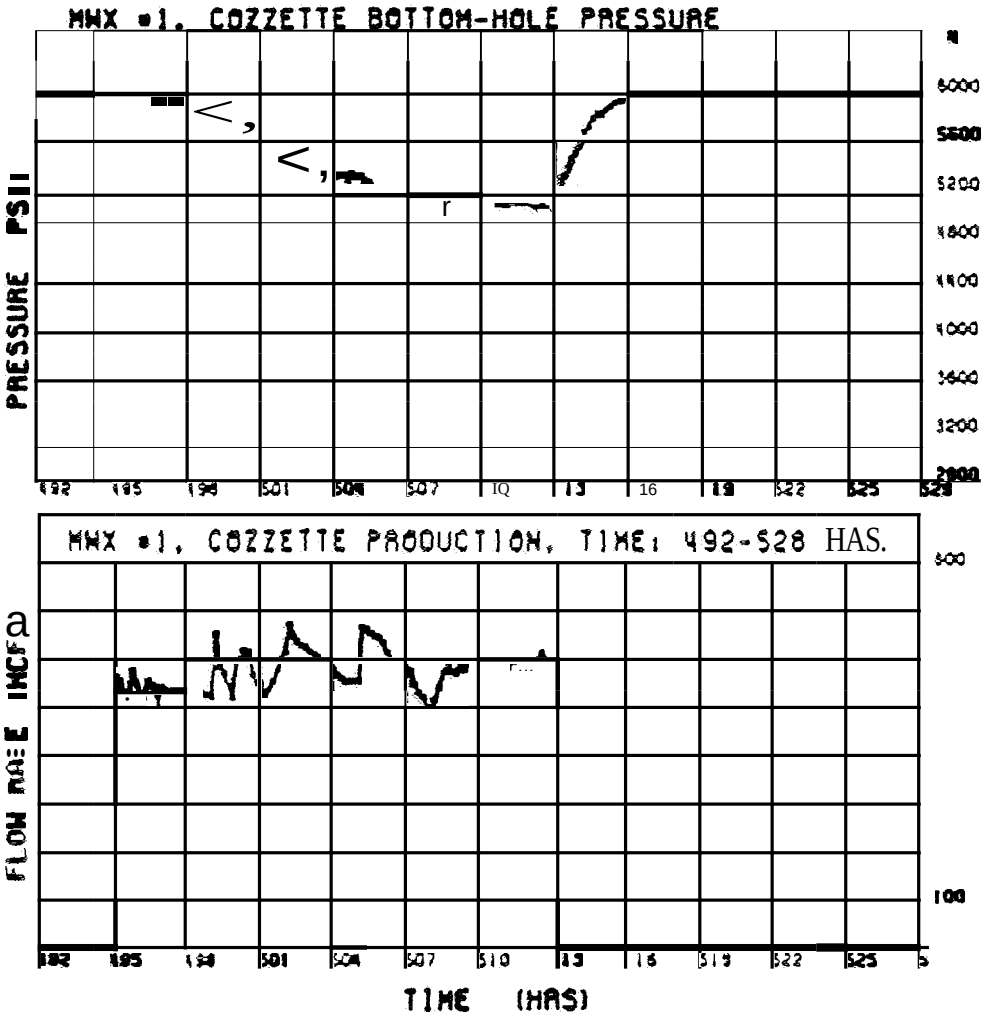

CER CORE # 56-18 (7868.0 FT)--
KLINKENBERG PERMEABILITY (MICRODARCIES
10
1
0.01
0
60
80
100

Reservoir and Well Parameters for the Cozzette Sandstone at the MWX Site

Formation Height,	h	30 feet
Formation Porosity,	ϕ_t	6.9 %
Formation Water Saturation,	Sw	40%
Reservoir Temperature,	T	230°F
Gas Viscosity,	μ	0.018cp
Initial Reservoir Pressure,	Pi	6,300 psi
Dry KHnkenberg Permeability,	kg	1.0μd
In Situ Klinkenberg Permeability,	kg	0.08μd
WeUbore Radius,	r_w	7.0 in.
Perforated Interval	7,855 - 7,892 feet MWX-l	
	7,830 - 7,850-60, 7,874-84 feet, MWX-2	
Tubing Length	7,820 feet MWX-l, MWX-2	


MAINTENANCE TEST RUN NUMBER - - LOW RHO DIGLE RUN NUMBER 2 DIGLE
PRESSURE IP
RATE (MCFD)

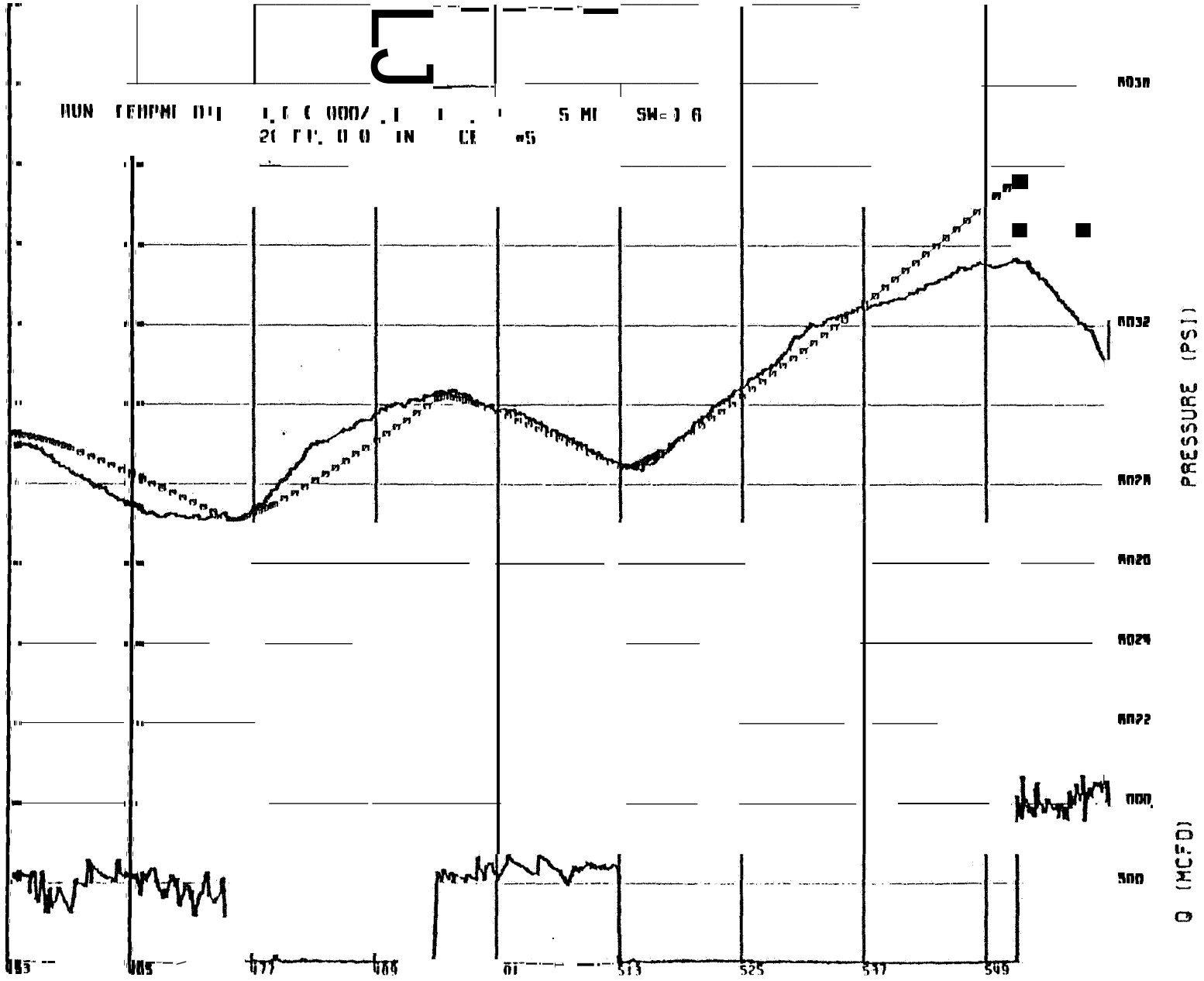

MMX •I. COZZETTE BOTTOM-HOLE PRESSURE
PRESSURE (PSI)
MMX •I. COZZETTE PRODUCTION
FLOW RATE (MCFD)
TIME (HRS)


MWX #1, COZZETTE BOTTOM-HOLE PRESSURE
PRESSURE PSII
6000
5600
5200
4800
4400
4000
3600
3200
2800
MWX #1, COZZETTE PRODUCTION, TIME: 492-528 HAS.
FLOW RATE MCF
600
100
TIME (HRS)

MULTI-WELL EXPERIMENT

- HOMOGENOUS PERMEABiliTY VARIATIONS
- SPACIAL VARIATIONS OF REDUCED PERMEABiliTY AT MWX #2
- REDUCED PERMEABILITY AT MWX #2
- ANSISOTROPIC PERMEABILITY
- BOUNDARY EFFECTS WITH ANSIOTROPIC PERMEABILITY
- VARIATIONS OF NATURAL FRACTURE DENSITY AND PERMEABlITY

UPPER COZZETTE, NTERFERENCE TEST, FLOW = WELL, PRESSURE =2 WELL



UPPER COZZETTE
SummaryIConclusions

- An orthogonal fracture network that exhibits a large permeability ratio distributed within a very tight sandstone matrix.

- Good pressure communication exists between the observation well and the naturally fractured reservoir, i.e., not much damage surrounding the well.

- The areal extent of the fracture system is large with no apparent boundaries closer than 1,000 feet.

- An av.erage reservoir permeability that lies in a.ranqs of 4 to 7md.

- Advanced stimulation techniques, including a propped hydraulic fracture would have little if any effect on enhancing production, and may have been counter productive.

UPPER COZZETIE
Summary/Conclusions

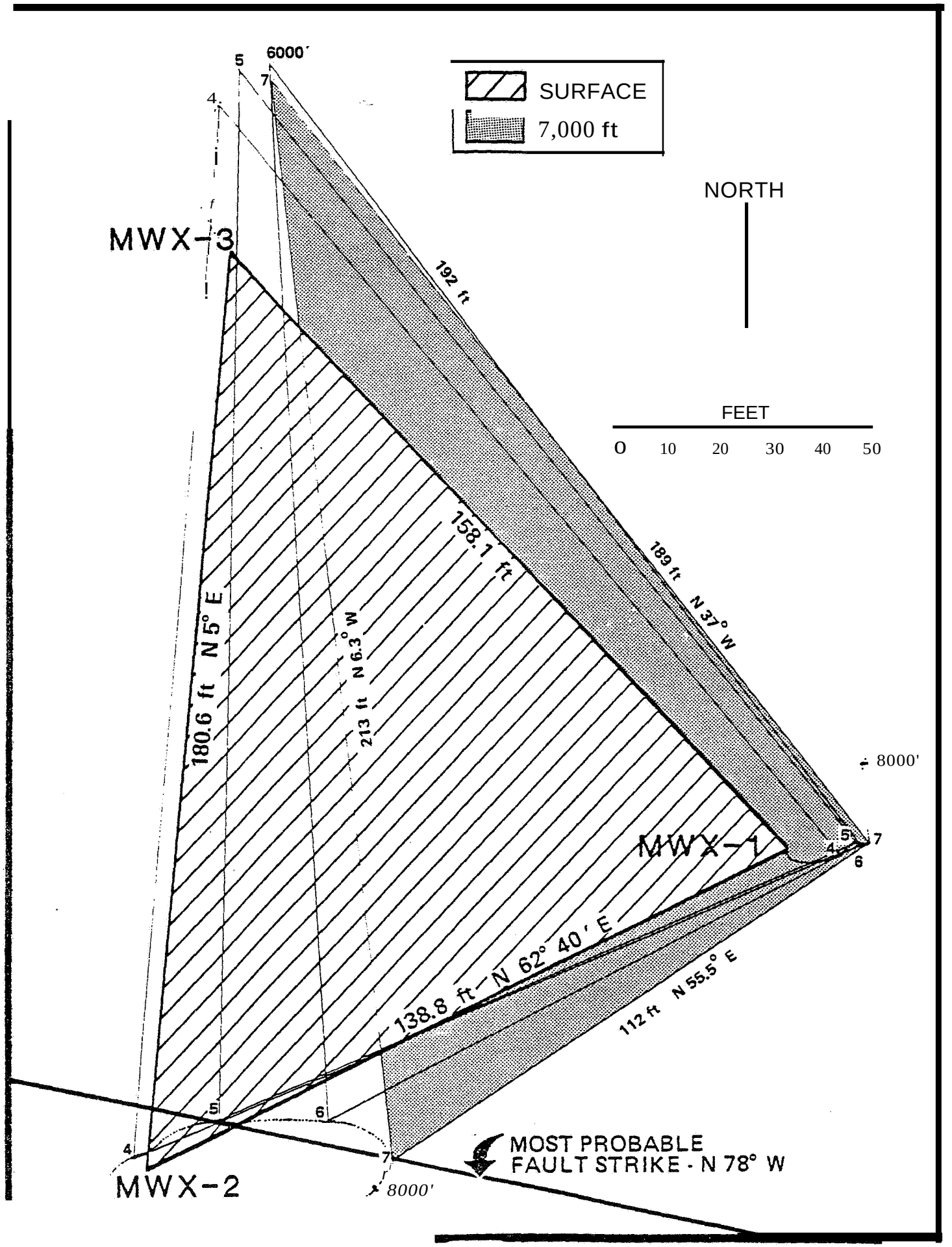
- Production from very tight matrix sandstones approximately 0.08μd can be substantial, provided there is an extensive natural fracture system connected to the welL

- Damage surrounding the wellbore can mask the productive capacity of even a highly overpressured very permeable system.

- Well test data from the production well may indicate conventional production history and not exhibit, in a reasonable time, a slope change on semilog plots that would suggest a dual porosity system.

- Average values for ·permeability obtained from the production well (200 to 300μd) may be considerably smaller than the more appropriate ones derived from an observation well (4 to 7md).

CER


6000'
SURFACE
7,000 ft
NORTH
FEET
0 10 20 30 40 50
MWX-3
192 ft
158.1 ft
189 ft N 37° W
180.6 ft N 5° E
213 ft N 6.3° W
8000'
MWX-1
138.8 ft N 62° 40' E
112 ft N 55.5° E
MOST PROBABLE
FAULT STRIKE - N 78° W
MWX-2
8000'

MWX-1

[illegible] Zone #2
(7230-[illegible] ft)

Perfs -[illegible]256-[illegible] [illegible] 4gm

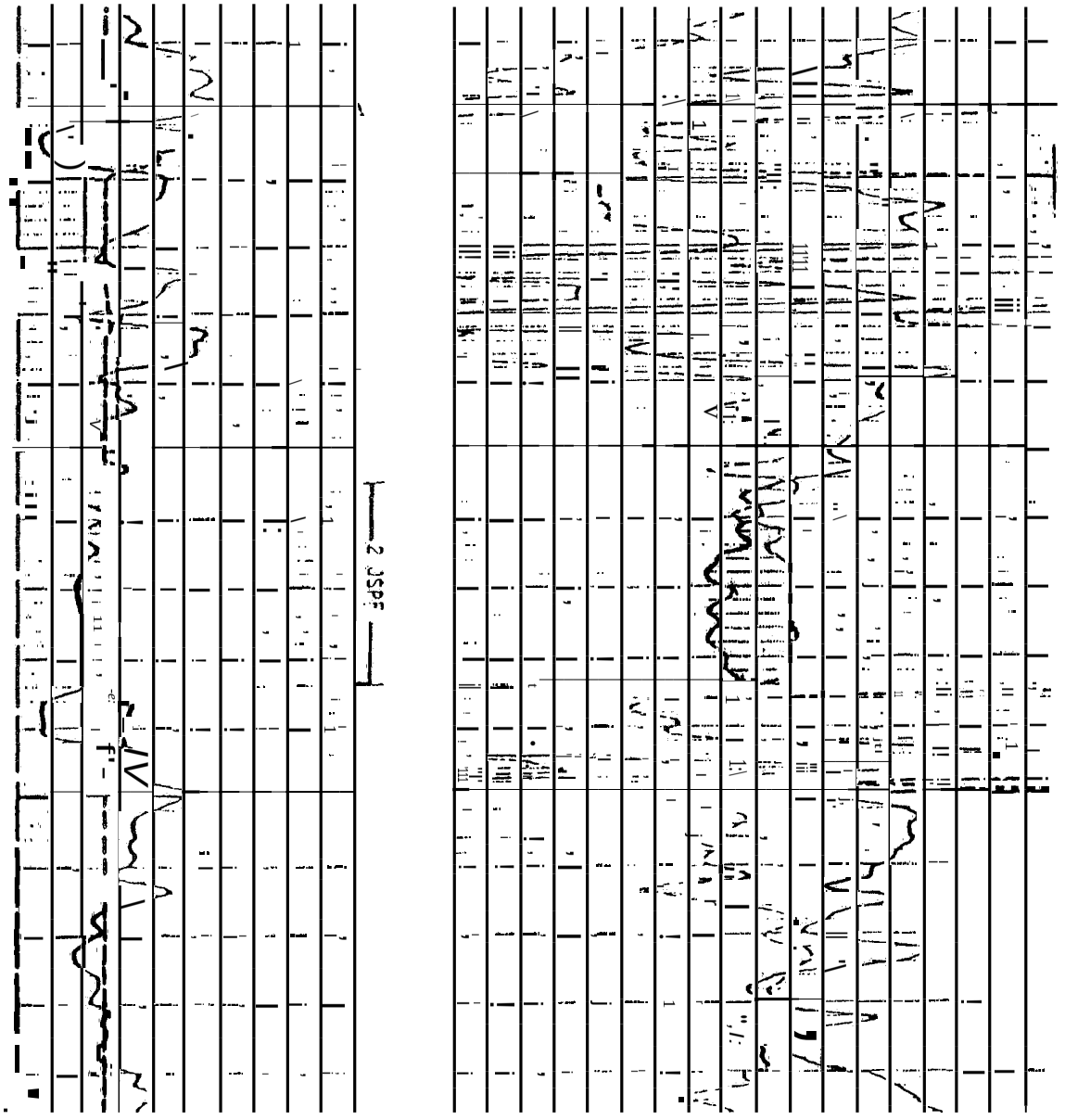
[illegible] h = 28 ft

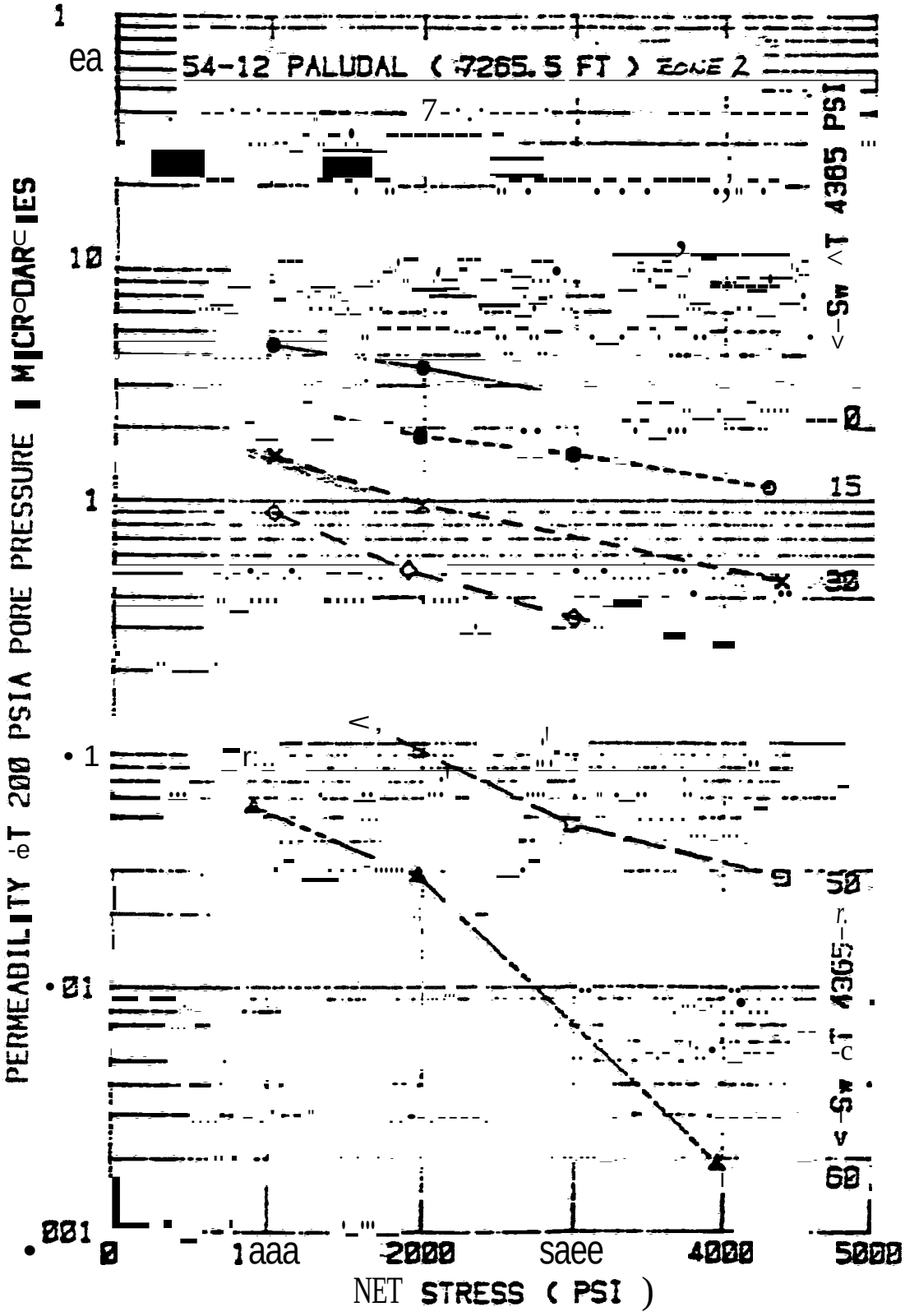
[illegible] at Po ϕ_L = 8.1%

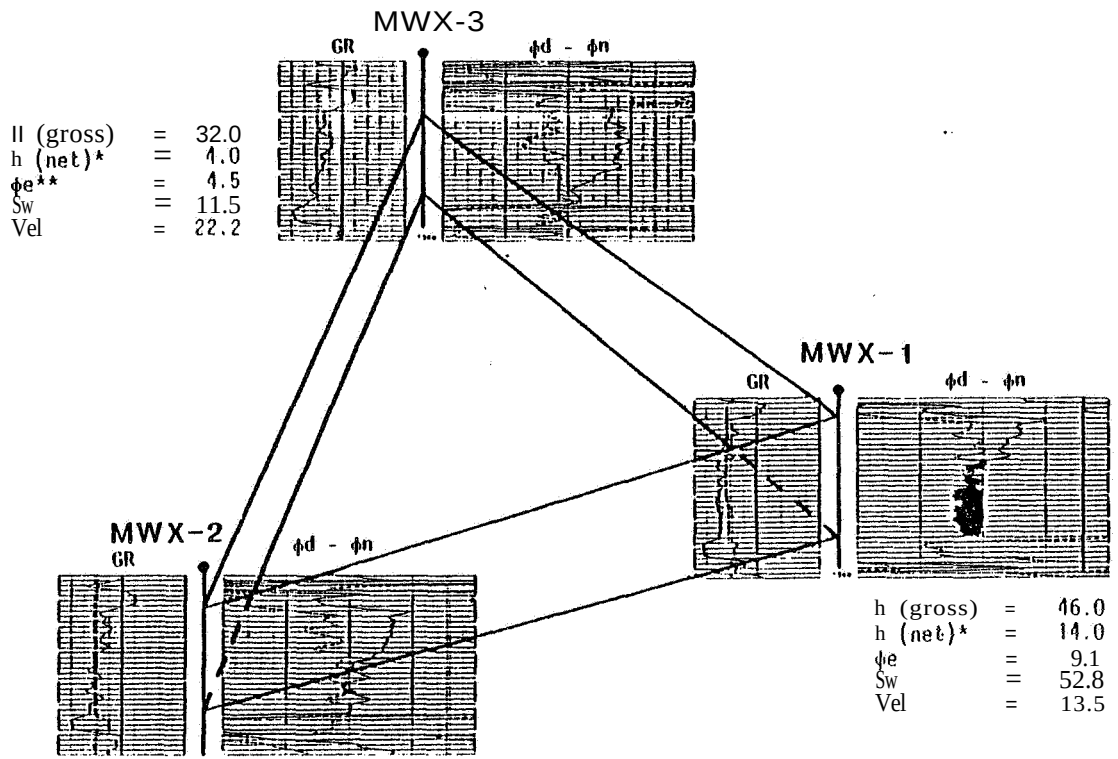
W[illegible] Sat. S_w = 31%

[illegible] k_g = 2.3μ

*MWX-2 Core derived average Klinkenberg permeability at 2000 psi net stress.




54-12 PALUDAL (7265.5 FT) ZONE 2
PERMEABILITY AT 200 PSIA PORE PRESSURE MICRODARCIES
NET STRESS (PSI)
0
2000
4000
5000
10
1
.1
.01
.001
15
50
60



II (gross)	=	32.0
h (net)*	=	1.0
φe**	=	1.5
Sw	=	11.5
Vel	=	22.2

h (gross)	=	16.0
h (net)*	=	14.0
φe	=	9.1
Sw	=	52.8
Vel	=	13.5

h (gross)	11.0
II (net)*	2.0
φe	5.9
Sw	61.7
Vcl	17.1

* IIased 011 Sw and 5)(0 computed curve soparntlen, Ilidlcatln!1 permeabllity developlllelll

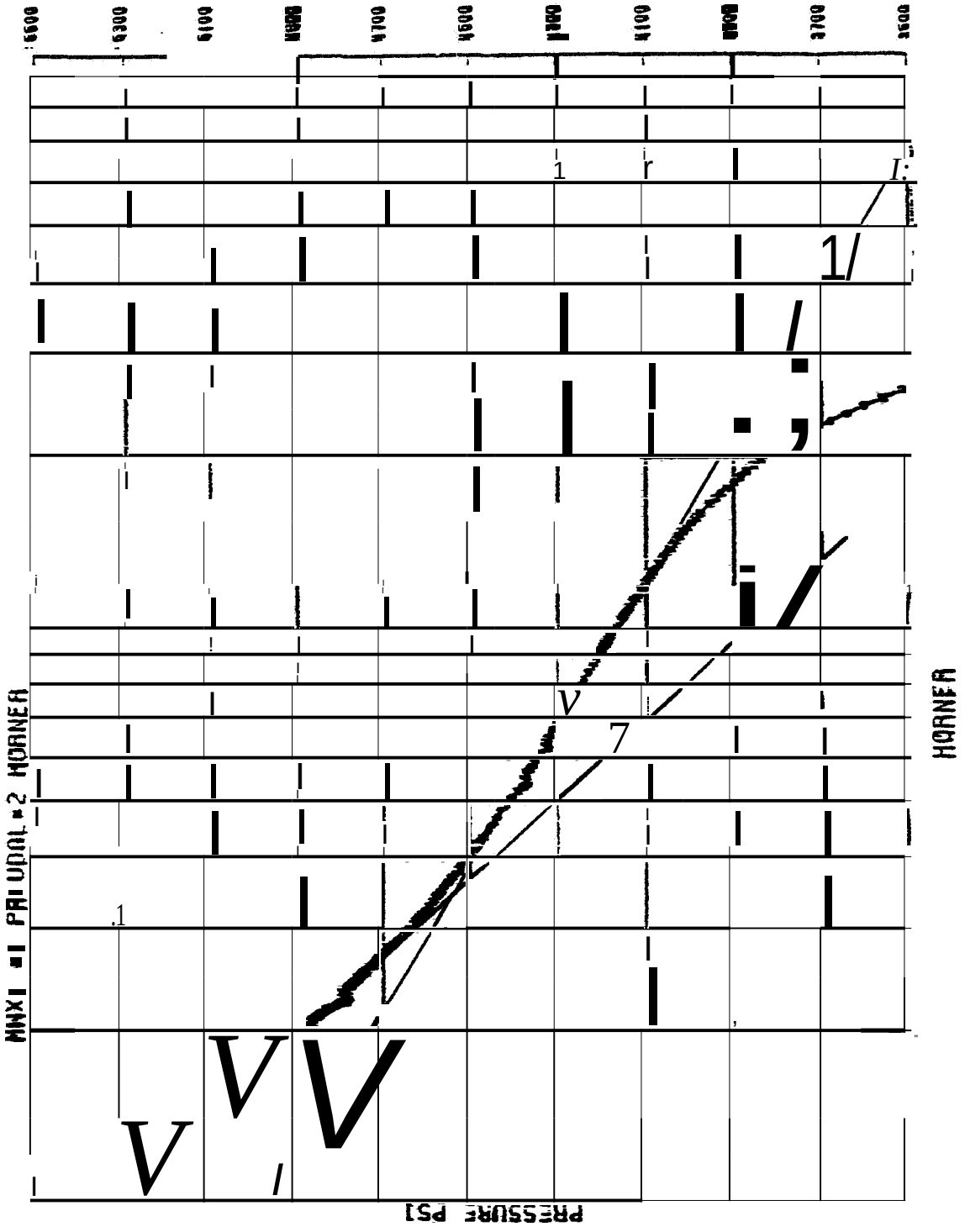
**Calculations are Ilrellllllillary resuHs based on manual rather than computer aliatvs Is

N
MW-3
MW-1
MW-2
213'
68'
112'
ZONE 2

MWX-1 PALUOAL ZONE 2

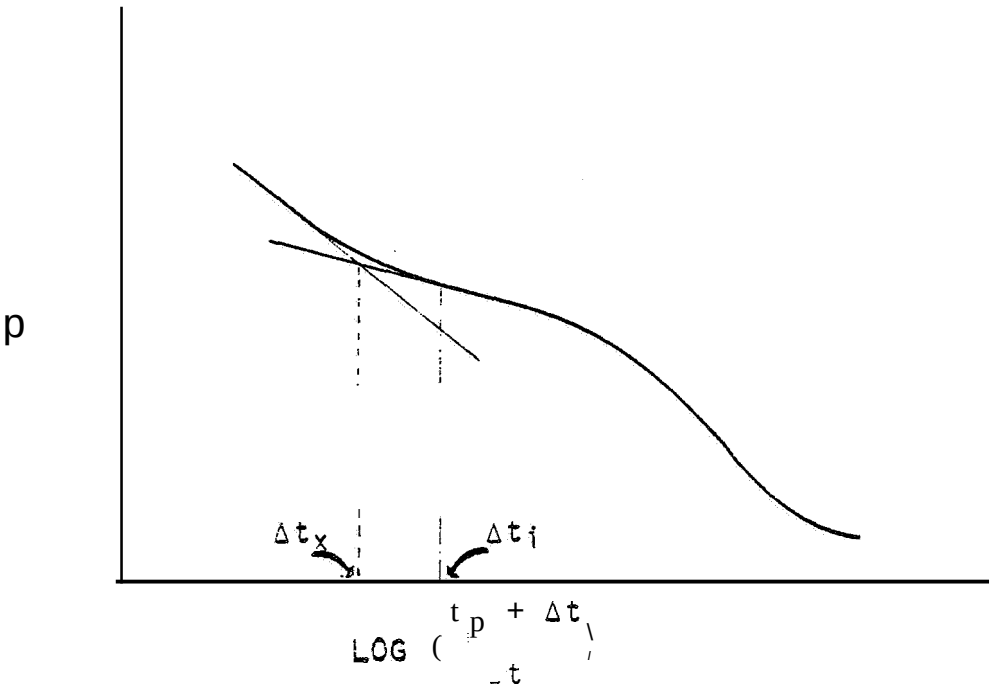
WELL TEST SCHEDULE

Date	Test	Preliminary rtesults
7/11-13	Stress Test	$\bar{\sigma}$ min = 0.88 psi/ft
7/19-25	Draudnun #1	tf ≈ 123 hrs. $\bar{q}$ = 140 MCFD
7/25-31	uutldup #1	Δt = 152 hrs, P_W = 4835 psi (Nearby boundary indicated)
7/31-0/·'	Orawdown #2	tf = 108 hrs, $\bar{q}$ = 165 MCFD
8/4-11	Buildup #2	Δt = 140 hrs, P_W = 4740 psi (Nearby boundary indicated)


MAXI =1 PRIUDAL =2 HORNER
HORNER
PRESSURE PSI

)

FAULT DISTANCE CL) CALCULATION



VAN POOLLEN (Δt_i)

$$L = \sqrt{\frac{0.00105\ K\ (\Delta t_i)}{\emptyset\ \mu\ C_t}}$$

Δt .- shut-in time (hrs)

$\emptyset$ =

K - 0.02 md

u = 0.02 c_p

C = 0.00012 psi^{-1}

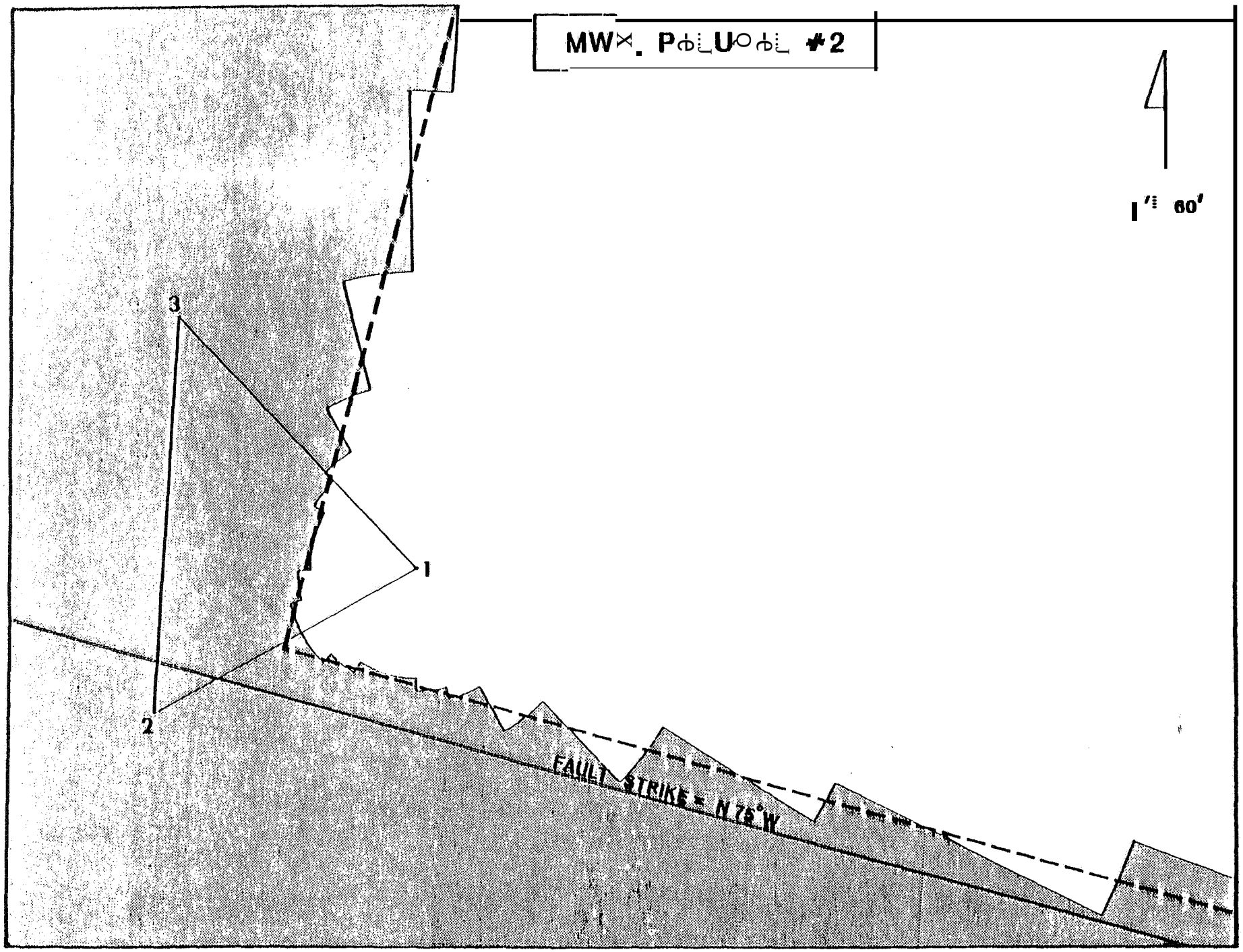
L = Distance (ft)

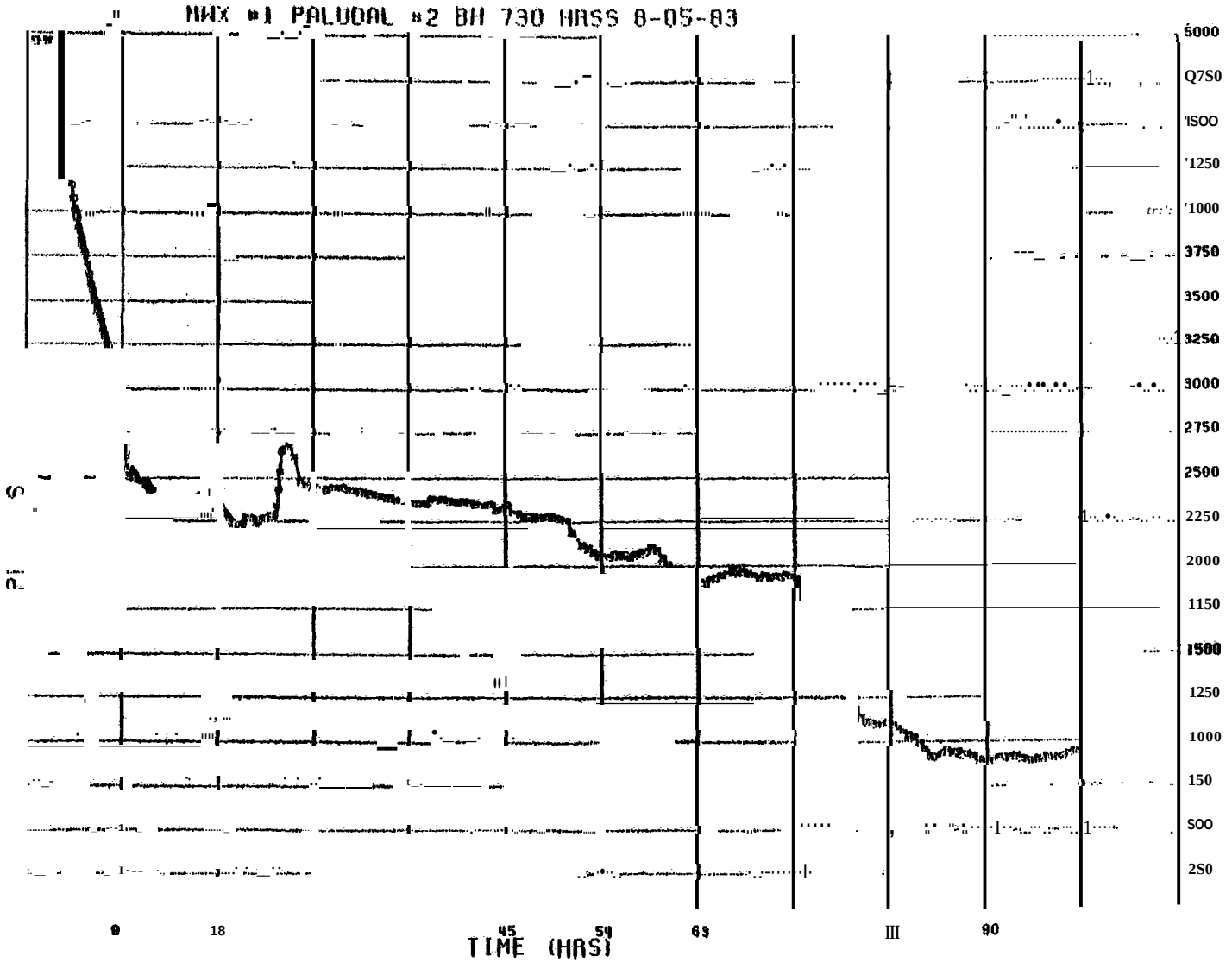
Paludal Zone #2

Reservoir Model Properties

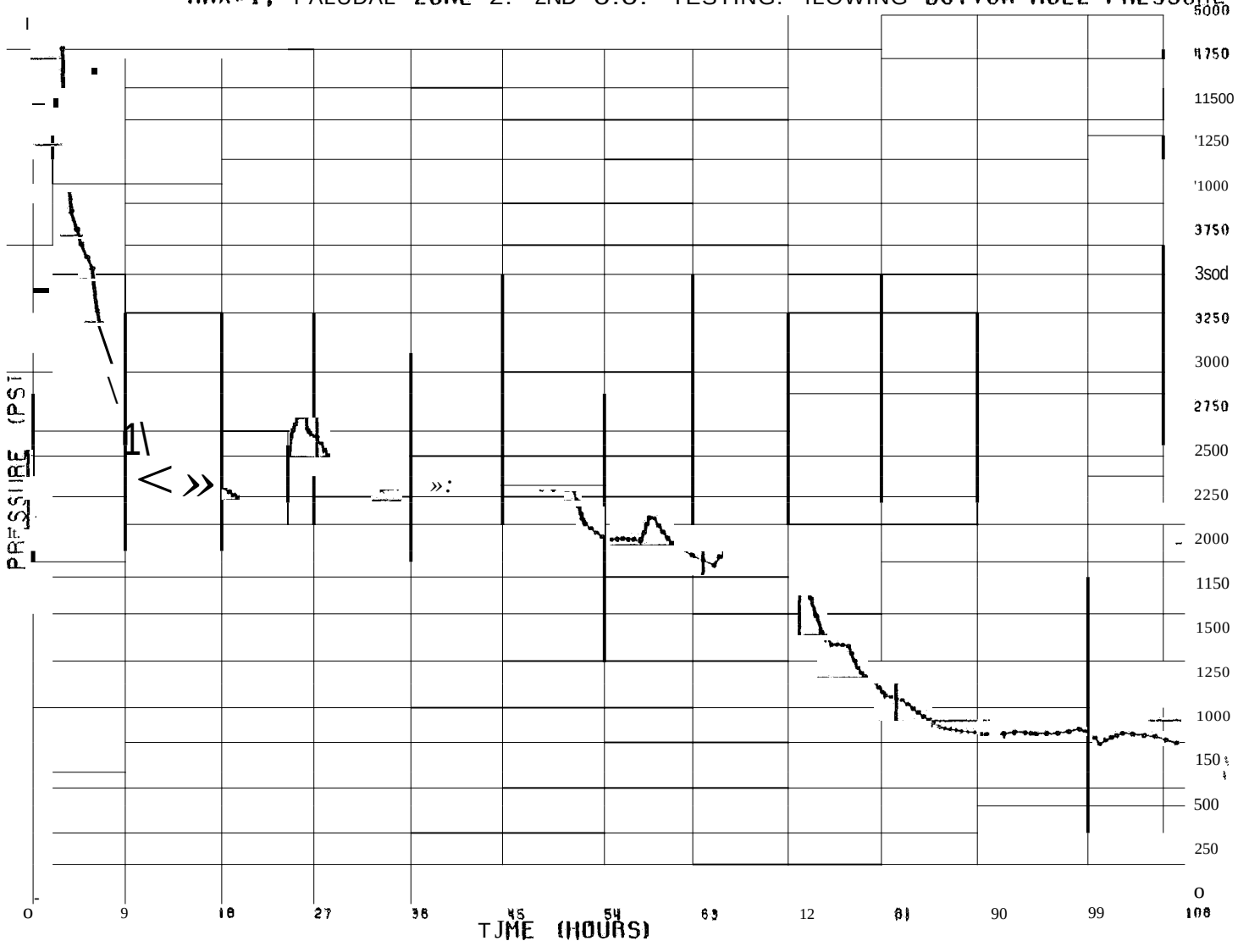
Perpendicular Boundary with 60 It from Wallbore, No Flow at Boundary.

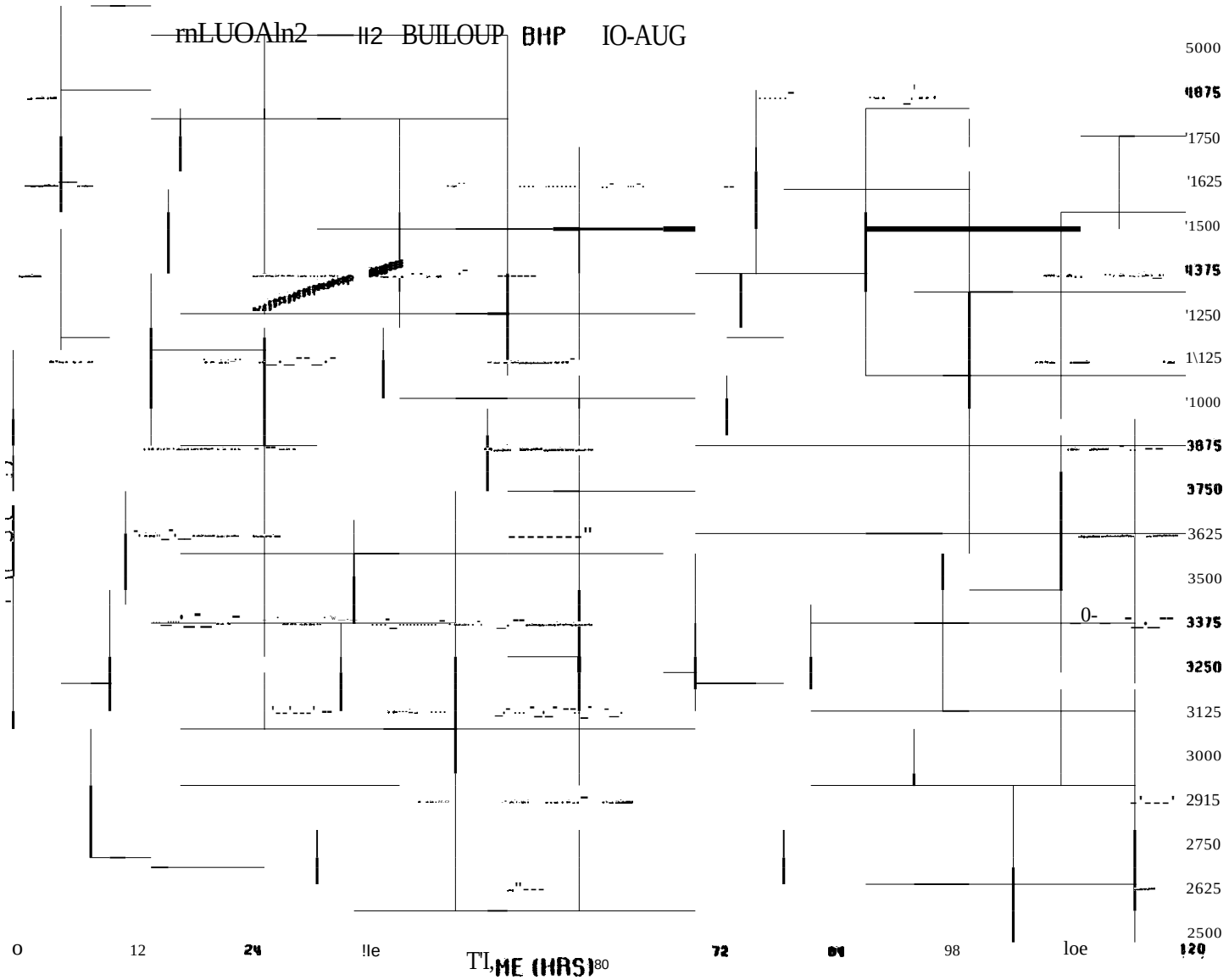
Reservoir Prassuru (Pres)	=	6,200 psi
Reservoir Temperature (Tres)	=	250"F
Avg. Ros. Temperature (Tavg)	=	160"f
Outer Boundary (110)	=	6.000 ft
Wellhoro Iladius (Rw)	=	0.3 ft
Tubing Inside Diamote. (11.0.)	=	2.269 inches
Wollhore Volumo (∇w)	=	140.02 ft^3
formation Permeability (K)	=	50 μd
Net Pay Height (H)	=	25 ft
Total Porosity (Ø)	=	0.00
Waler Saturation [Sw]	=	0.46
Skin facto.(S)	=	0
Formation Turbulent faciO. (β)	=	6.5×10^{12}


MW-. PLUG #2
1" = 60'
3
1
2
FAULT STRIKE = N 75°W


MWX #1 PALUDAL #2 BH 730 HRSS 8-05-83
5000
Q7S0
'ISOO
'1250
'1000
3750
3500
3250
3000
2750
2500
2250
2000
1150
1500
1250
1000
150
SOO
2S0
0
18
45
54
63
III
90
TIME (HRS)

MWX#1, PALUDAL ZONE 2. 2ND O.O. TESTING. fLOWING BOTTOM HOLE PRESSURE



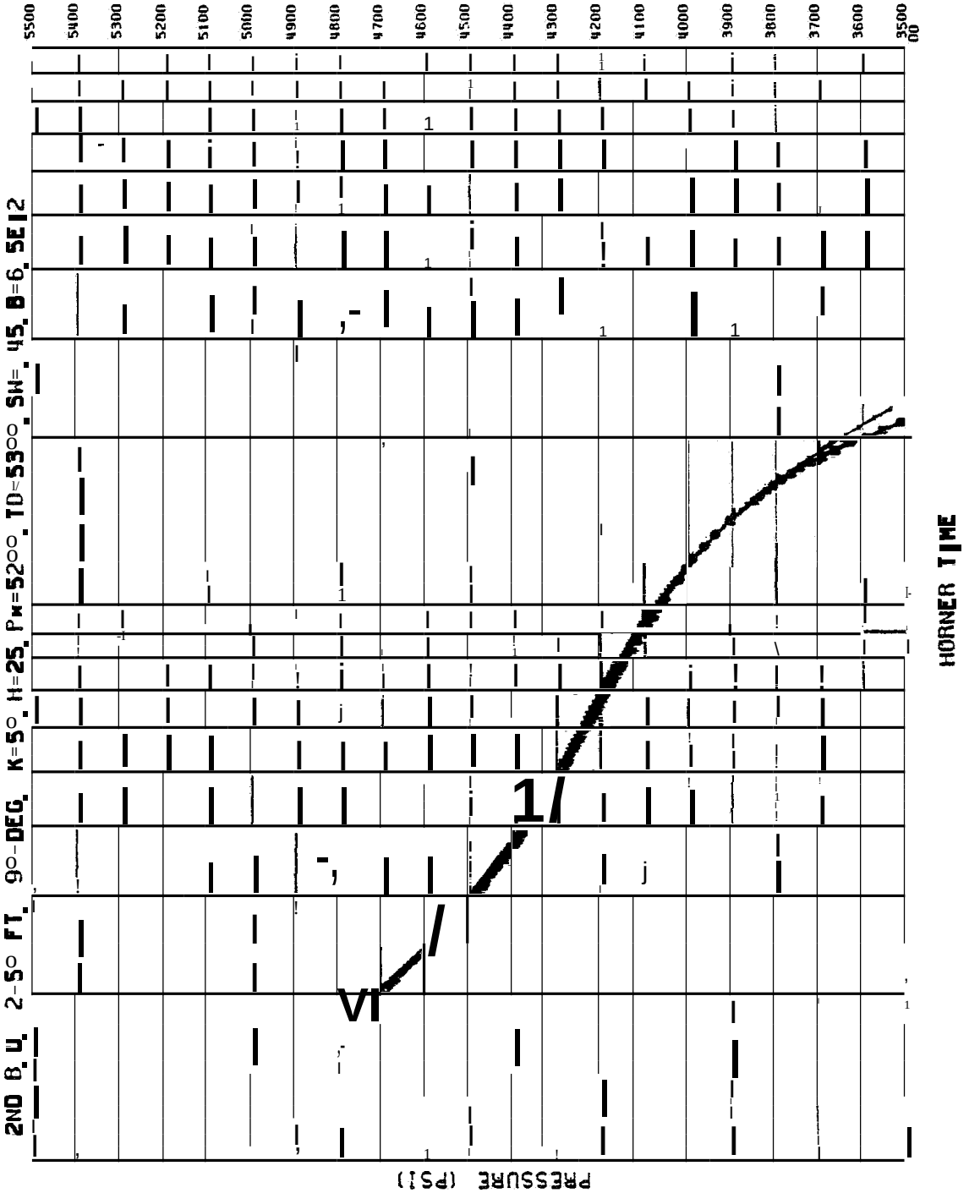

rnLUOAln2 — II2 BUILOUP BHP IO-AUG
5000
4875
4750
4625
4500
4375
4250
4125
4000
3875
3750
3625
3500
3375
3250
3125
3000
2915
2750
2625
2500
0
12
24
!le
TIME (HRS)
80
72
98
loe
120

MWX*1, rnr.uoru ZONE 2. 2ND B.U. TEST. SIIUT-IN BOTTOM 1I0LE rRESSURE

5000
4875
4750
4625
4500
4375
4250
4125
11000
30J5
3750
3625
3500
3375
3250
3'25
3000
2875
2150
2625
2500

0 6 12 III 24 30 36 112 1'0 lil 60 811 72 71\ 84 1111 IIIi 102 100 11' 120

TIME HOURS)


2ND B.U. 2-5° FT. 9°-DEG. K=5° H=25. Pw=52°°. TD=53°° SW=. 45. B=6. 5E12
5500
5400
5300
5200
5100
5000
4900
4800
4700
4600
4500
4400
4300
4200
4100
4000
3900
3800
3700
3600
3500
00
PRESSURE (PSI)
HORNER TIME

MULTI-WEll EXPERIMENT

- CORE $k \simeq 1 \mu d$
- RESERVOIR MODEL DATA k 50 d
- APPARENT OBSERVATION OF FAULT NEARMWX #2
- DISTINCTIVE TWO BOUNDARY SYSTEM

CER

MULTI-W 'MENT

PAI

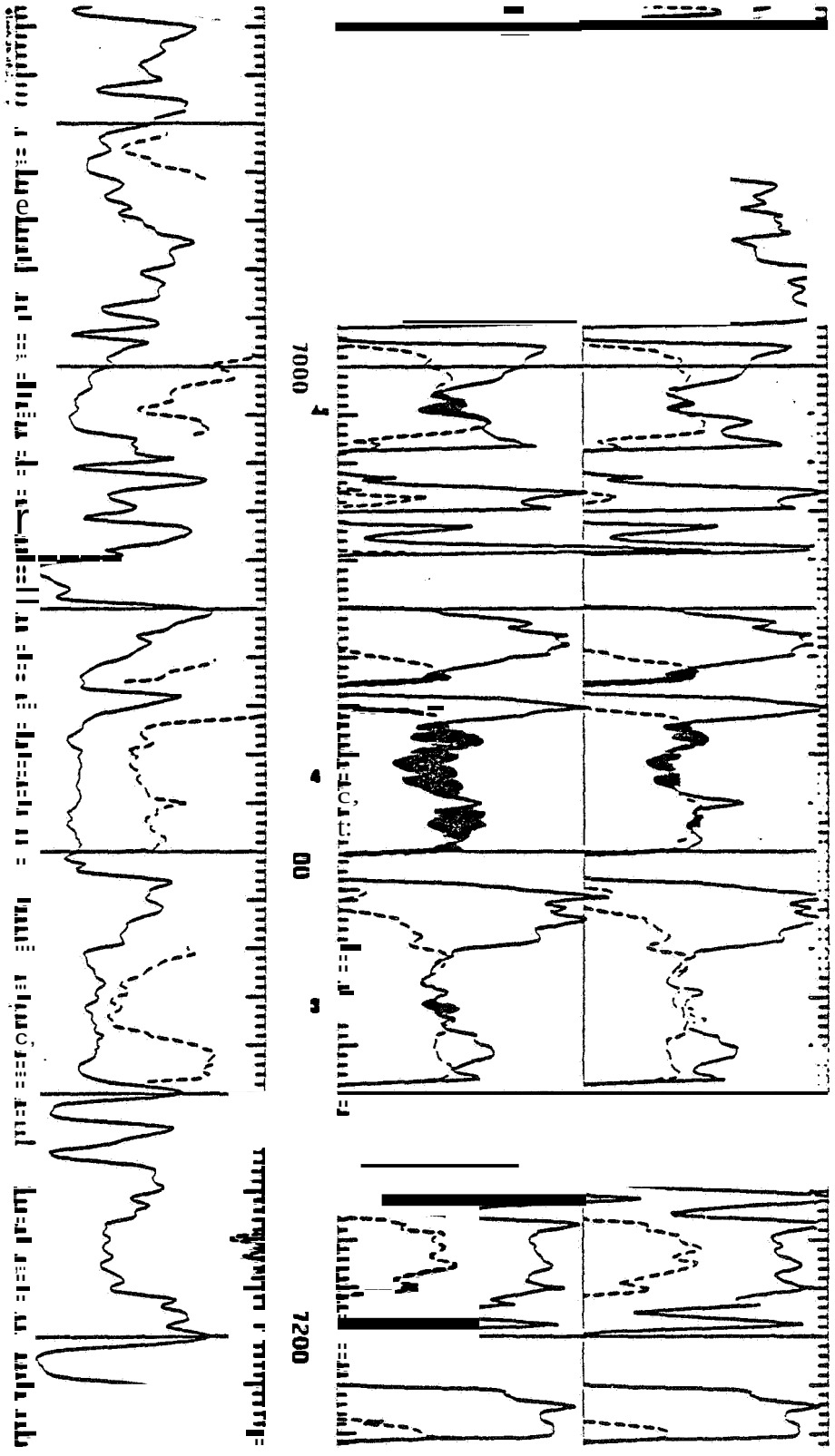
3

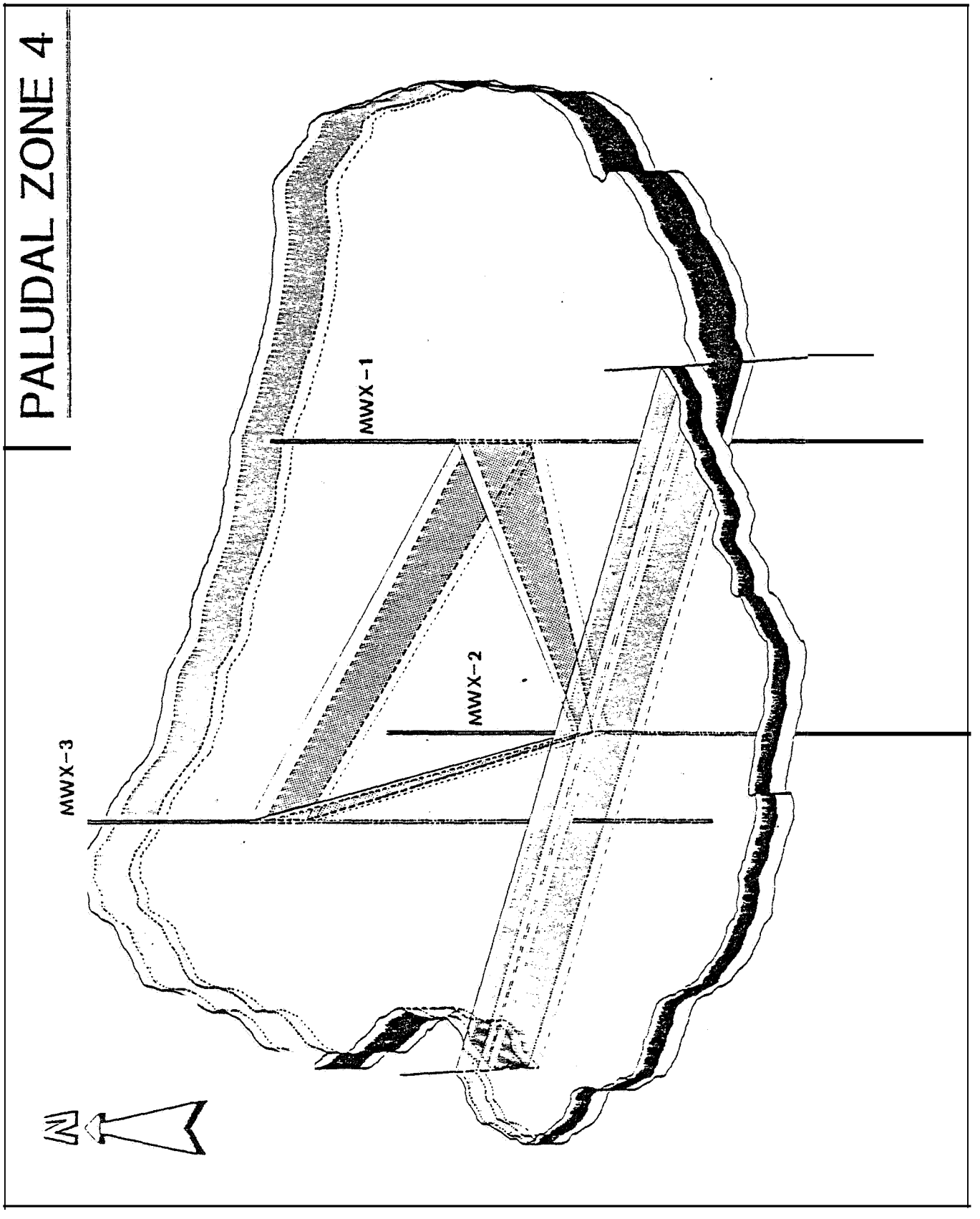
NE

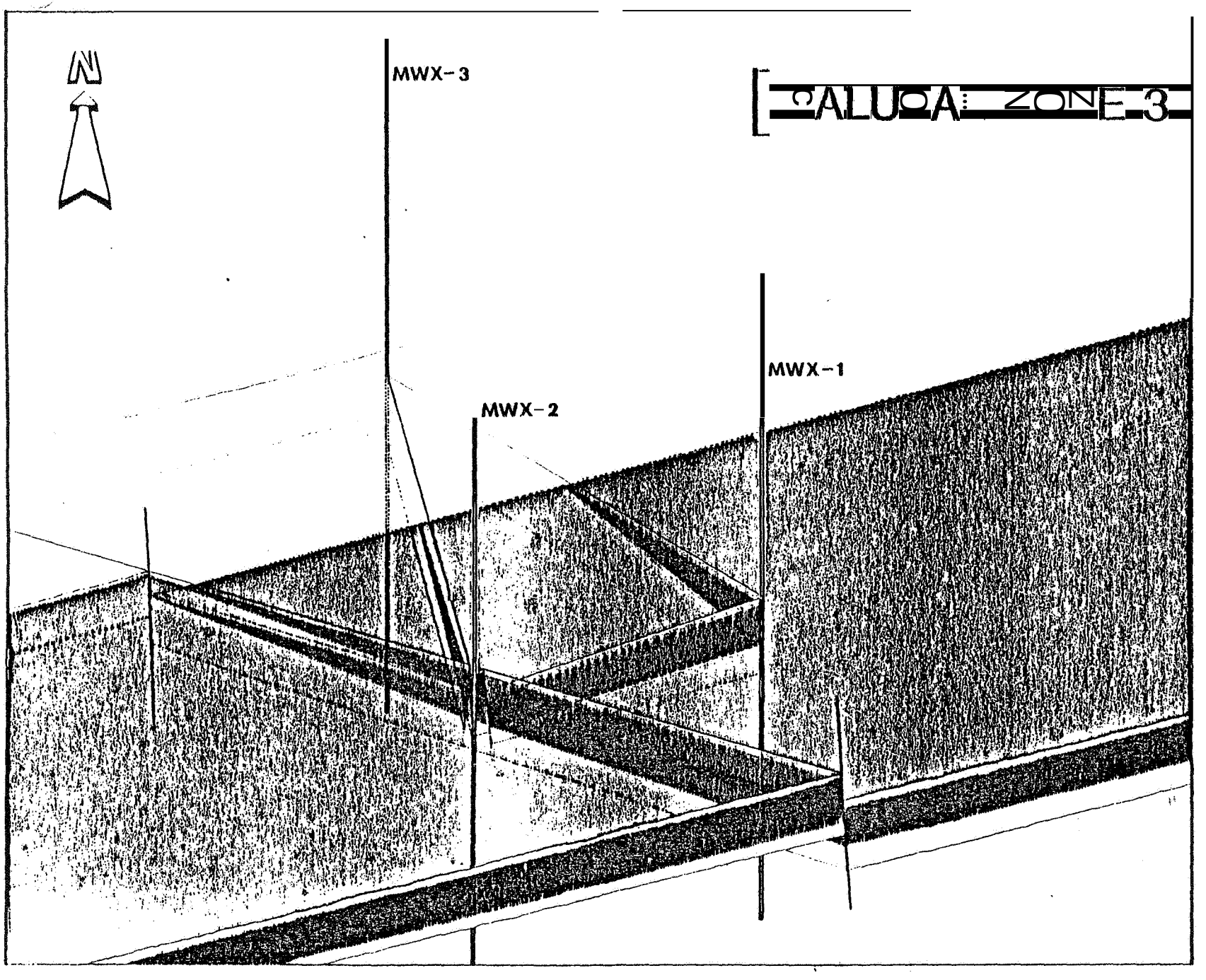
CER

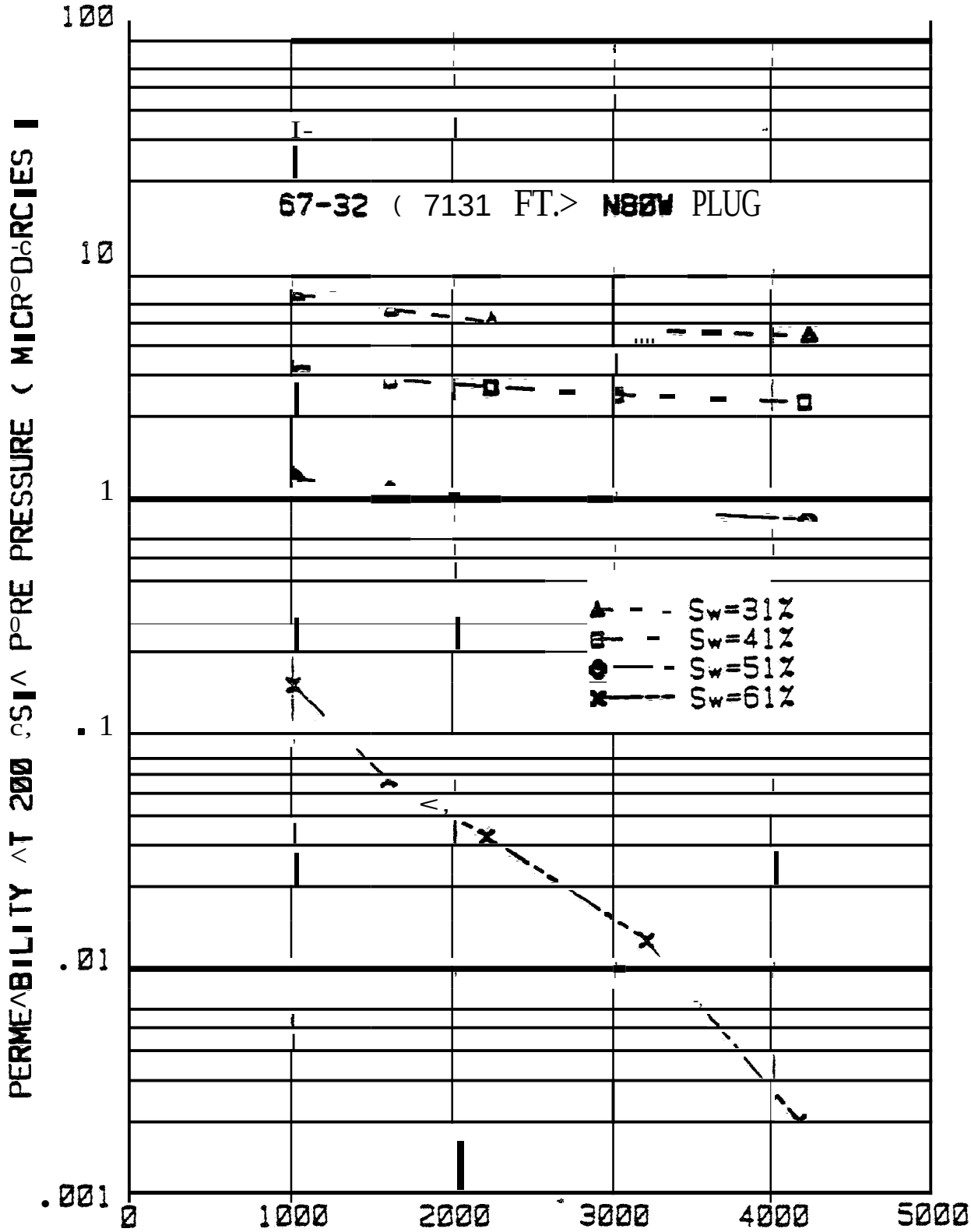
MWX #1

PALUDAL ZONES #3-4



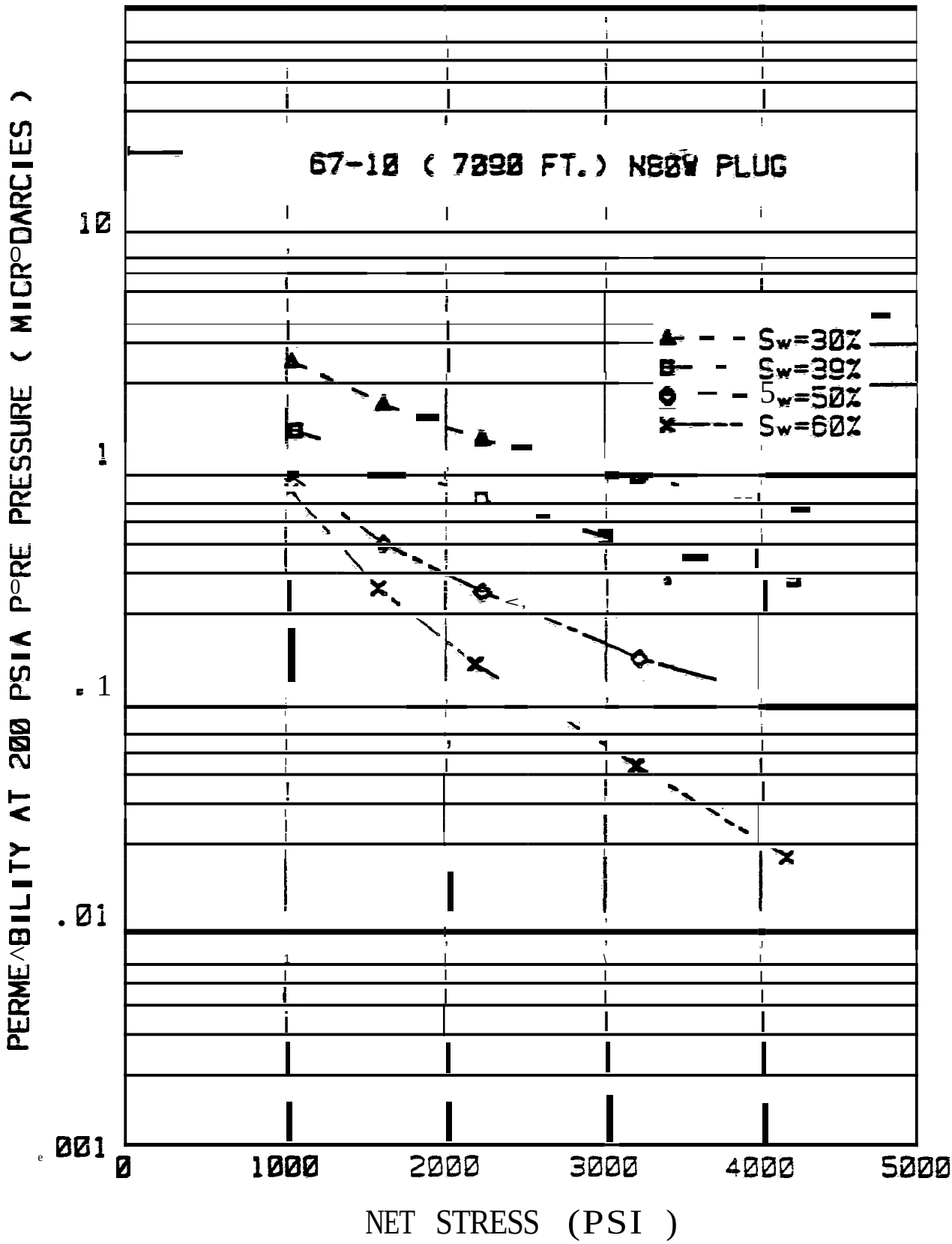

PALUDAL ZONE 4
MWX-3
MWX-2
MWX-1
N


N
MWX-3
MWX-2
MWX-1
SALUDA ZONE 3



MWX-3 PALUDAL ZONE 3

HIGHEST PERMEABILITY ZONE



MWX-3 PALUDAL ZONE 4

CORE AND LOG

DERIVED RESERVOIR CHARACTERISTICS

PALUDAL ZONES 3 & 4

Zone 3

ϕ_t,	total matrix porosity	10.3%
S_w,	water saturation	46.0:
k_g,	relative matrix gas permeability (S_w = 45%)	3.0μd
h,	productive channel thickness	
	MWX-1	8 £t
	MWX-2	12 £t
	MWX-3	ø £t
μ,	gas viscosity	.02cp
T,	reservoir temperature	210°r

Zone 4

ϕ_t,	total matrix porosity	10.2%
S_w,	water saturation	46.0:
k_g,	relative matrix gas permeability (S_w ·	< 0.5μd
h,	productive splay thickness,	
	MWX-1	18 £t
	MWX-2	2 £t*
	MWX-3	14 ft
	ga.s viscosity	.02cp
	reservoir temperature	2l0°'F

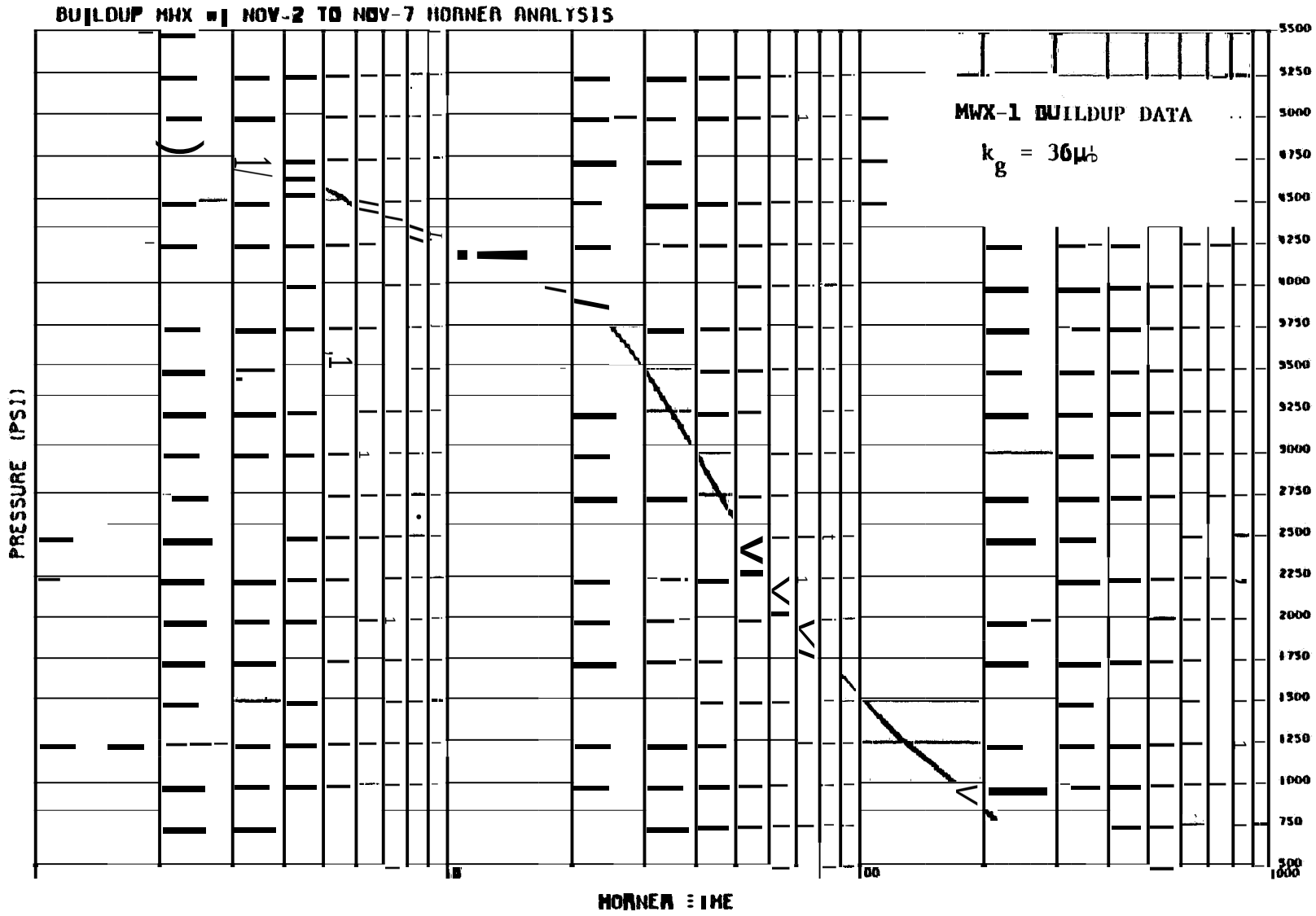
* Fault intersects Zone 4 in MWX-2 and masks true reservoir thickness. This value is probably a minimum.

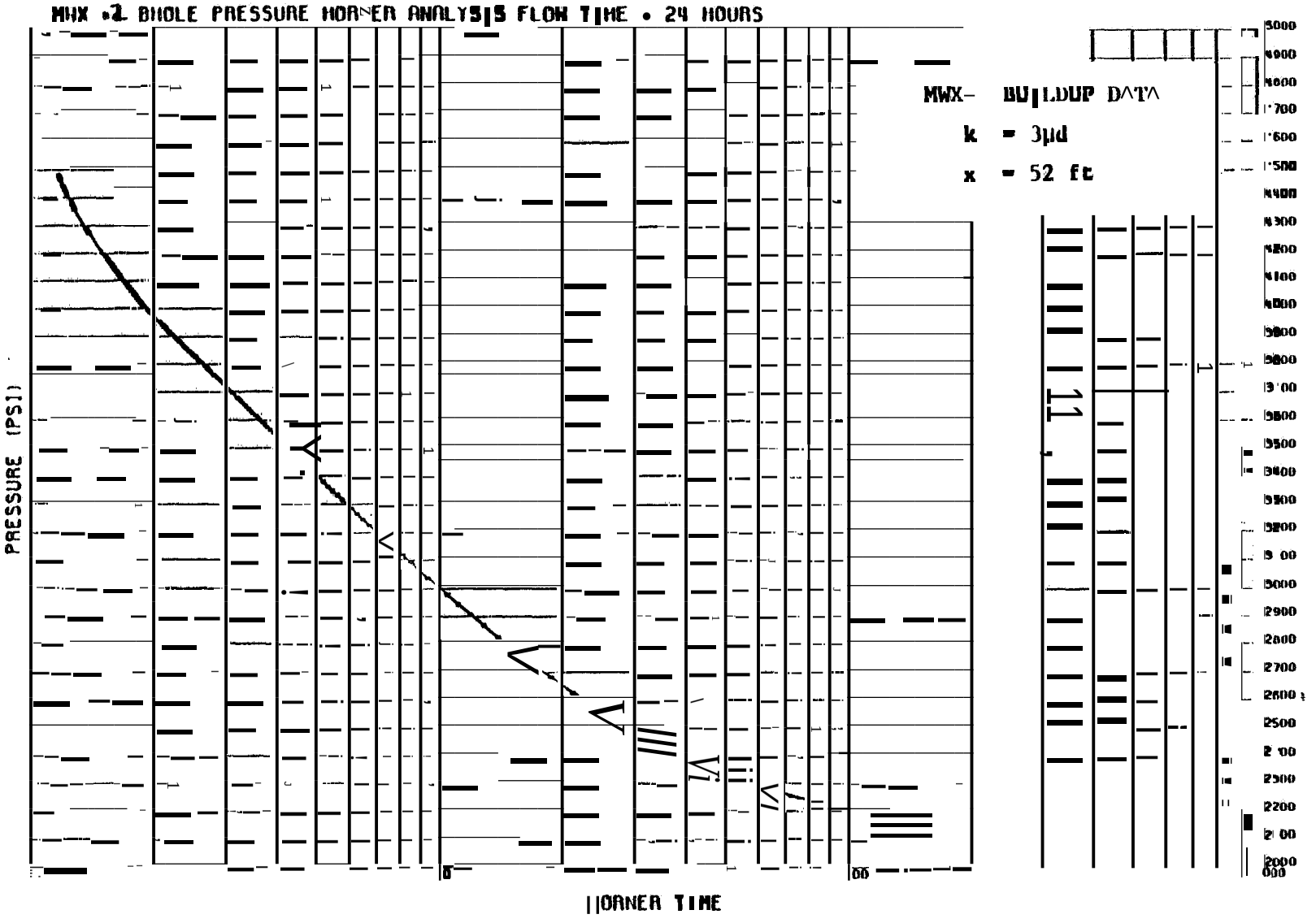
MULTI-WELL E

PALUDAL ZONE

- MWX-1 Well Test
- MWX-2 Well Test (Fault)
- MWX-1 3 Well Interference

CER


BUILDUP MWX #1 NOV-2 TO NOV-7 HORNER ANALYSIS
MWX-1 BUILDUP DATA
k_g = 36μ
PRESSURE (PSI)
HORNER TIME
5500
5250
5000
4750
4500
4250
4000
3750
3500
3250
3000
2750
2500
2250
2000
1750
1500
1250
1000
750
500
1000


MWX -2 BHOLE PRESSURE HORNER ANALYSIS FLOW TIME = 24 HOURS
MWX- BUILDUP DATA
k = 3μd
x = 52 ft
PRESSURE (PSI)
HORNER TIME

MWX-1, PALUDAL ZONE 3-4

RESERVOIR EVALuATiON

IU.NUMERICALSIMULATION

MODEL / REMARK	Single Phase Radial Model	Single Phase Dual Porosity Model
Pre Frac Reid Data Match	K = 0.025 md, (Average Value) H = 40 ft AOF = 250 MCFO	RESERVOIR PARAMETER: K matrix = 0.003 md K nat. Irac = 1625 md Spacing = 20 ft Width = 0.001 in

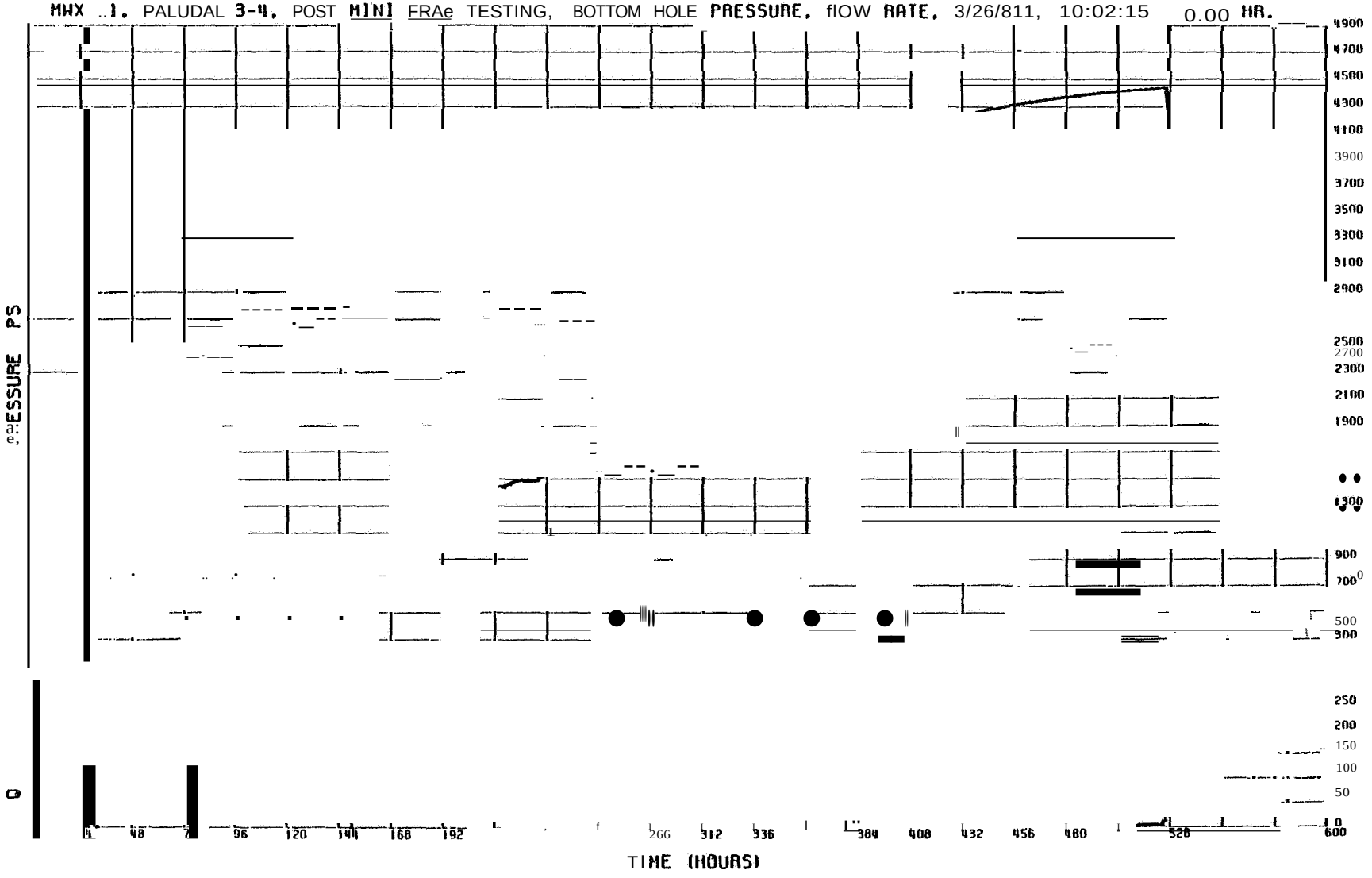
PHASE I

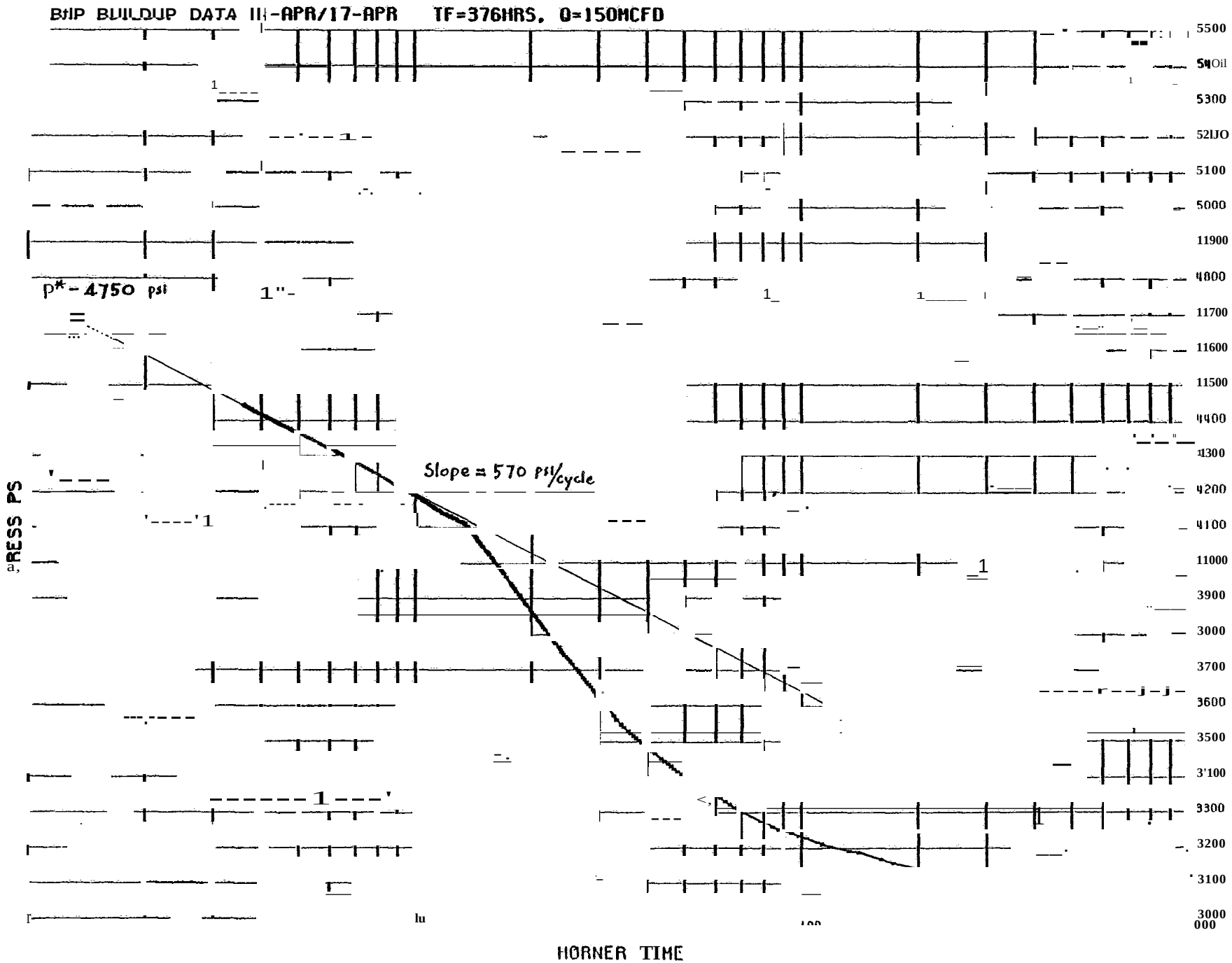
POST FRACTURE WELL TESTING OBJECTIVES

(UNPROPPED FRACTURE)

- DETERMINE PRODUCTION ENHANCEMENT MWX-1
- ESTIMATE UNPROPPED FRACTURE CONDUCTIVITY|LENGTH
- EVAIUATE FORMATION DAMAGE FROM FRAC FLUID
- DETERMINE CRITERIA PHASE II INTERFERENCE TEST

MHX ..1. PALUDAL 3-4. POST MINI FRAe TESTING, BOTTOM HOLE PRESSURE. flOW RATE. 3/26/811, 10:02:15 0.00 HR.




BHP BUILDUP DATA 11-APR/17-APR TF=376HRS, Q=150MCFD
p*=4750 psi
Slope = 570 psi/cycle
PRESS PS
HORNER TIME
5500
5300
5100
5000
11900
11700
11600
11500
11300
4200
4100
11000
3900
3000
3700
3600
3500
3300
3200
3100
3000

MWX-1, PALUDAL ZONE 3-4

FRACTUREEVALUATION

I. FIELD OATA

(A) Pre Frac Data

- 7 Days Flow, Q = 250 MCFD
- 5300 psi .. 800 psi

(8) Phase I Frac Data

- 6 Days Flow, Q = 200 .MCFD
- 5300 psi - 700 psi

(C) Phase II Frac Data

MWX-1, PALUDAL ZONE 3-4

FRACTURE EVALUATION

II. CONVENTIONAL ANALYSIS

(A) Pre FracData

K matrix = O.003md {Laboratory Core Analysis}

H = 40 ft {Log Analysis}

Well Testing

KH = 1.0 md - ft

S = 0.59

(B) Phase I Frac Data

KH = 0.64 md-ft

S = -3.79

KeD = 2.5

KfW = 71.4 md-ft

MULTI-WEll EXPERIMENT

- PRE FRAC kh::: 1.Omd ft
- POST FRAC kh≃0.6 md ft
- APPROXIMATELY 85% LIQUID RECOVERY
- FRACTURE CAPACITY≃71 md ft
- SLIGHT RESERVOIR DEGREDATION
- UNPROPPED FRACTURE WAS PERMEABLE

CER

MWX-1,'PALUDAL ZONE 3-4

FRACTUREEVALUATION

III. NUMERICAL SIMULATION

MODEL / REMARK	Single Phase Radial Model	Single Phase Dual Porosity Model
Pre Frae Field Data Mateh	K= 0.025 md, (Average Value) H=40ft AOF = 250 MCFD	RESERVOIR PARAMETER: .K matrix = 0.003 md K nat. frac = 1625 md Spacing = 20 ft Width = 0.001 in
Phase II Frae Evaluation	K =0.003 rnd (Matrix Value) L frac = 432 ft W frac = 0.6 in K frac = 1.0 D Q = 2500 MCFD 10 days 5300 psl- 1700 psi AOF = 900 MCFD	RESERVOIR PARAMETER: Same As Above L frac = 400 ft W frac = 0.6 in K frac = 100 D Q = 1350 MCFD 7 days 5300 psi· 110 psi
		RESERVOIR PARAMETER: Same As Above L frac = 400 ft W frac = 0.06 in Kfrac=50D Q = 985 MCFD 7 days 5300 psi • 1134 psi

MULTI-WELL EXPERIMENT

3≥4

3.0μd	36μd
Frac - MWX#3 (10 days)	Frac» MWX#3 (8.5 days)
Frac - MWX#2 (11 days)	Frac - MWX#2 (1.0 days)

CER

title: MWXSTIMULATION DESIGN

or9anization: SANDIA NATIONAL LABS

principal investigator: N. WARPINSKI

period of performance: CONTINUING

funding: PART OF MWX
APPROXIMATE 1.0FTE RATE

STIMULATION GOALS

DETERMINE FRACTURE GEOMETRY IN RELATION TO LENS ORIENTATION AND EXTENT

CAN LENSES NOT IN CONTACT WITH THE WELL BE INTERSECTED AND PRODUCED

EFFICIENTLY PRODUCE A SERIES OF LENSES

EUALUATE GEOLOGIC/RESERUOIRPARAMETERS

EUALUATE STIMULATION FACTORS

EUALUATE NEW STIMULATION TECHNIQUES

0.

STIMULATION DESIGN

RESERUOIR DATA (COREJLOGS)

GEOLOGIC DATA (CORE) LOGS) SEISMIC)

WELL TESTING (INTERFERENCE)

IN SITU STRESS

ASSEMBLE DATA SET

DEFINE GOALS AND OBJECTIUES

DESIGN TREATMENT

MINIFRAC FOR FINE TUNING

RESERUOIR FACTORS

PERMEABILITY AND POROSITY

- **FLU ID LEAI(OFF**
- **BACK STRESSES**
- **DAMAGE**

ROCK PROPERTIES

- YOUNG'S **MODULUS (FRAC WIDTH)**
- POISSON'S **RATIO**
- **FRACTURE TOUGHNESS**

RESERUO I.R **PRESSURE**

PALUDAL
RESERUOIR PARAMETERS

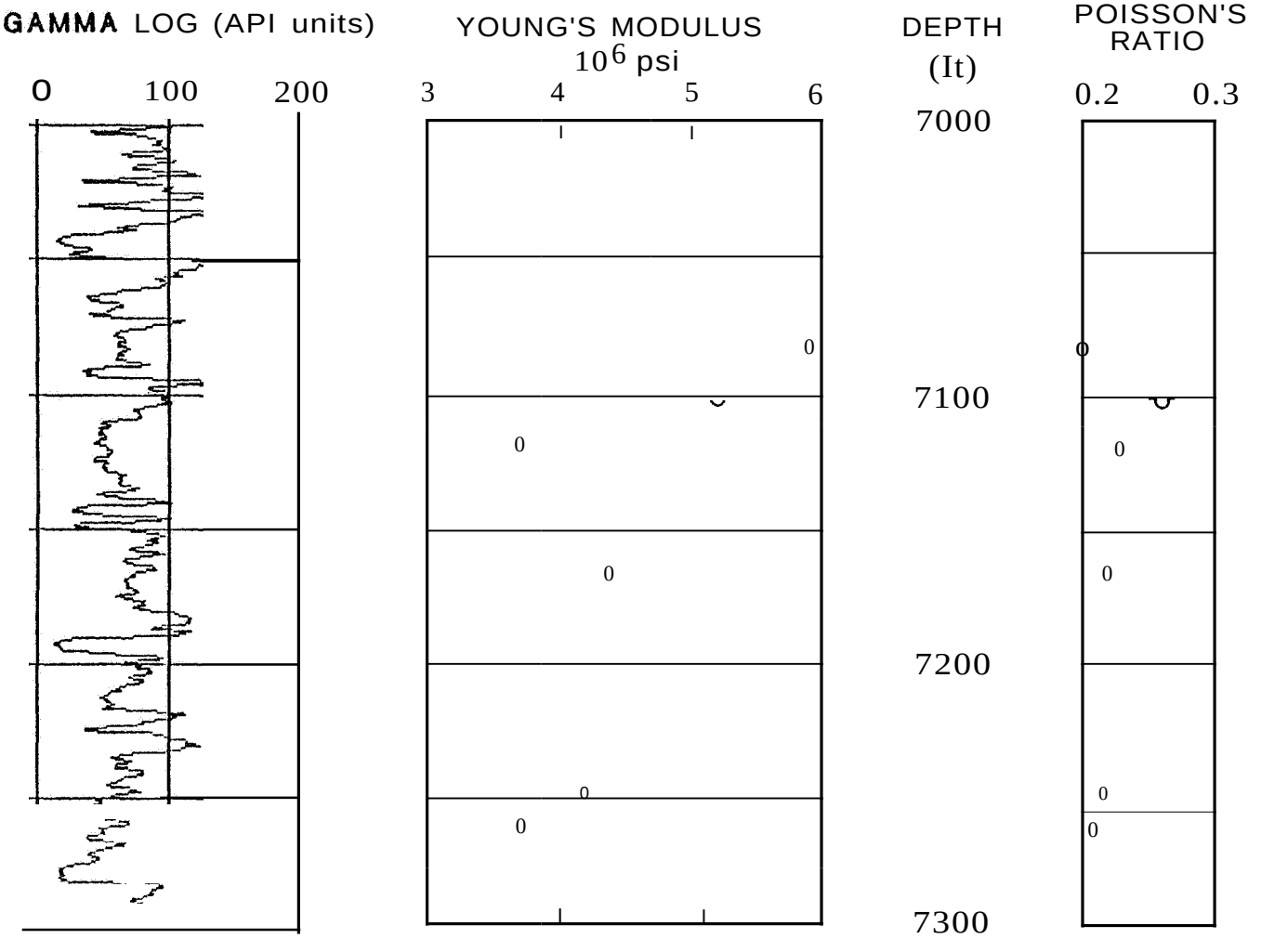
MATRIX PERMEABILITY = 1-2 MICRODARCYS

POROSITY = 8-12 %

WATER SATURATION = 35-40 %

BULK PERMEABILITY = 20-50MICRODARCYS

PALUDAL ROCK PROPERTIES



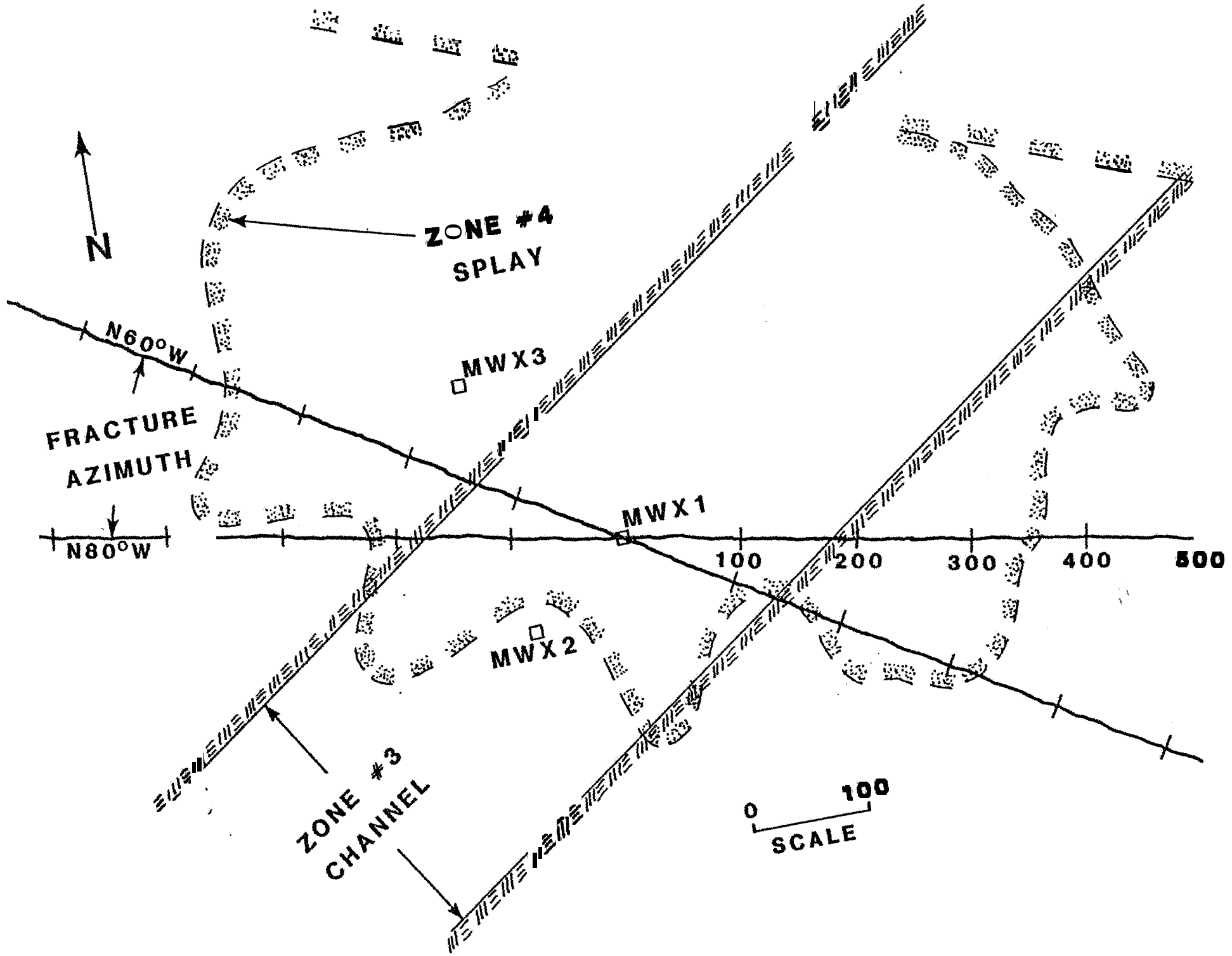
GEOLOGIC FACTORS

SAND MORPHOLOGY
- TYPE (CHANNEL, MEANDER BELT)
- SIZE (WIDTH)

STRUCTURAL FEATURES

NATURAL FRACTURES

DEPOSITIONAL ENUIRONMENT
- ROCKS ABUTTING PAY ZONE
- STRESS CONTRASTS


N
ZONE #4
SPLAY
N60°W
FRACTURE
AZIMUTH
N80°W
MWX3
MWX1
MWX2
100
200
300
400
500
ZONE #3
CHANNEL
0
100
SCALE

IN SITU STRESS

FRACTURE HEIGHT (CONTAINMENT)

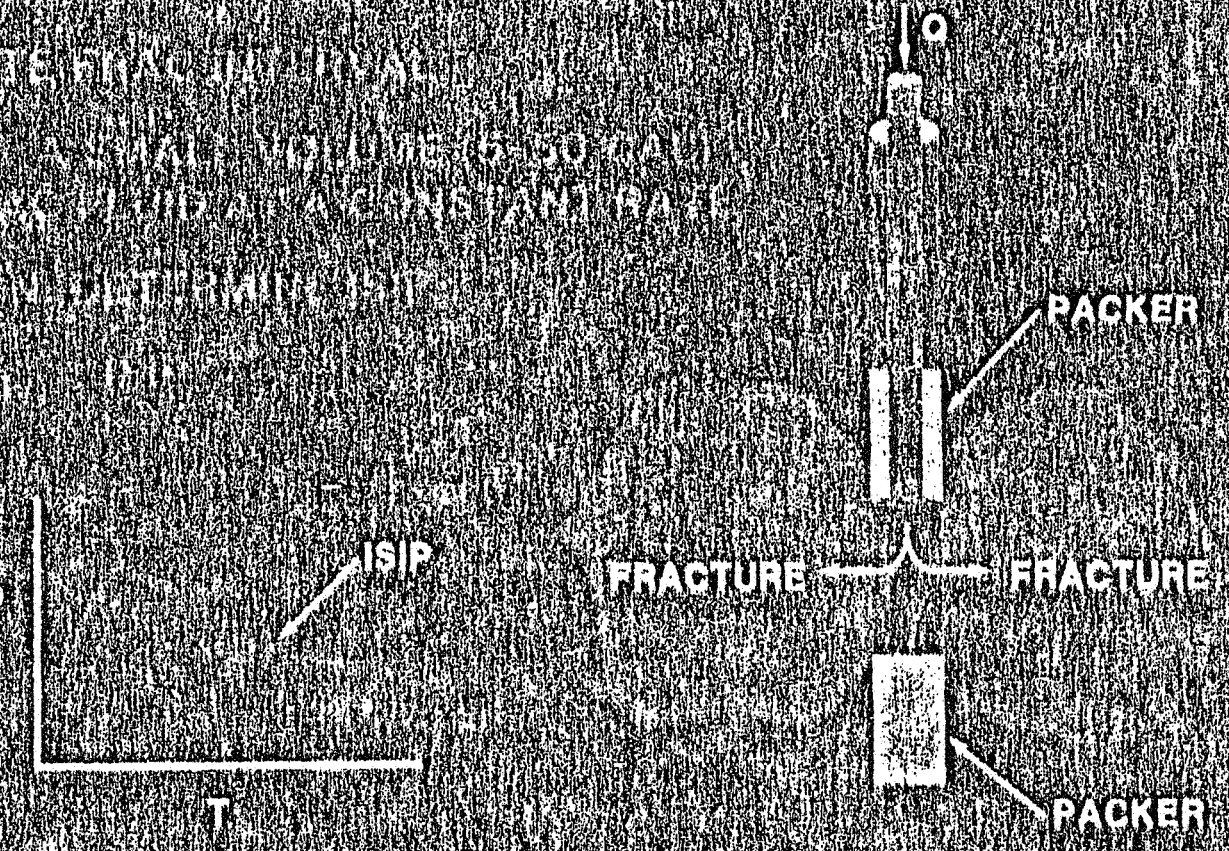
TREATMENT PRESSURE ANALYSIS

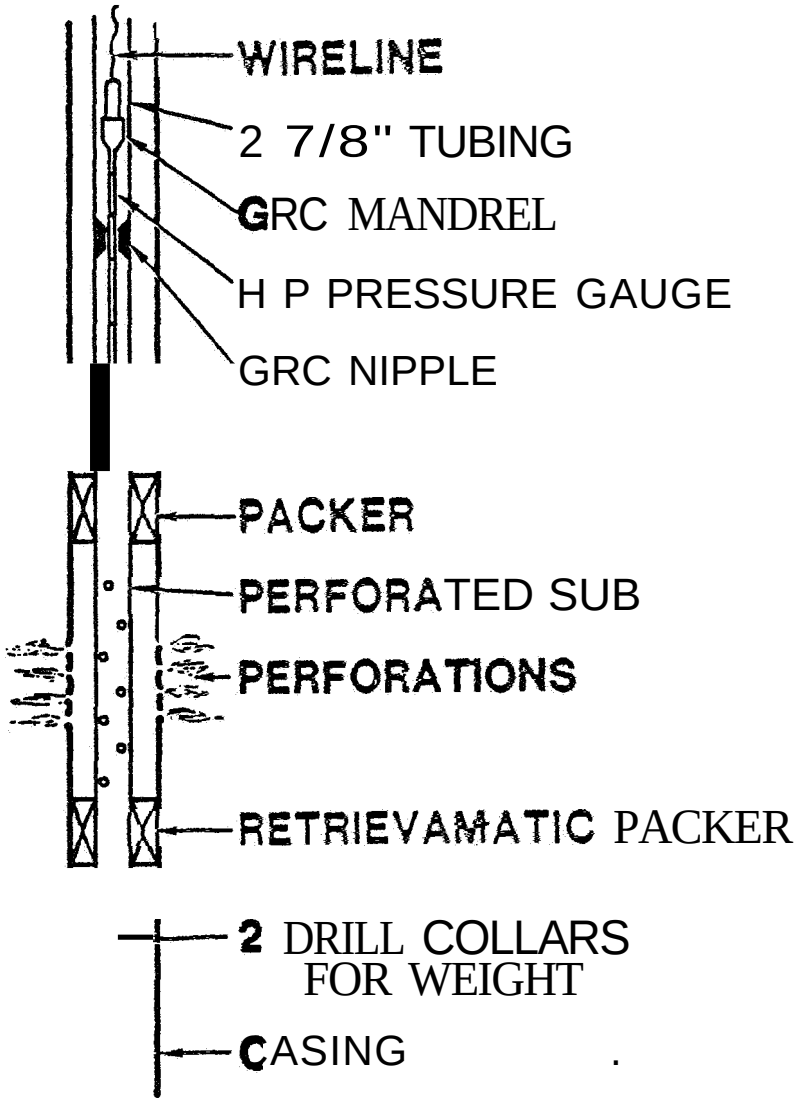
ABNORMAL TREATING CONDITIONS

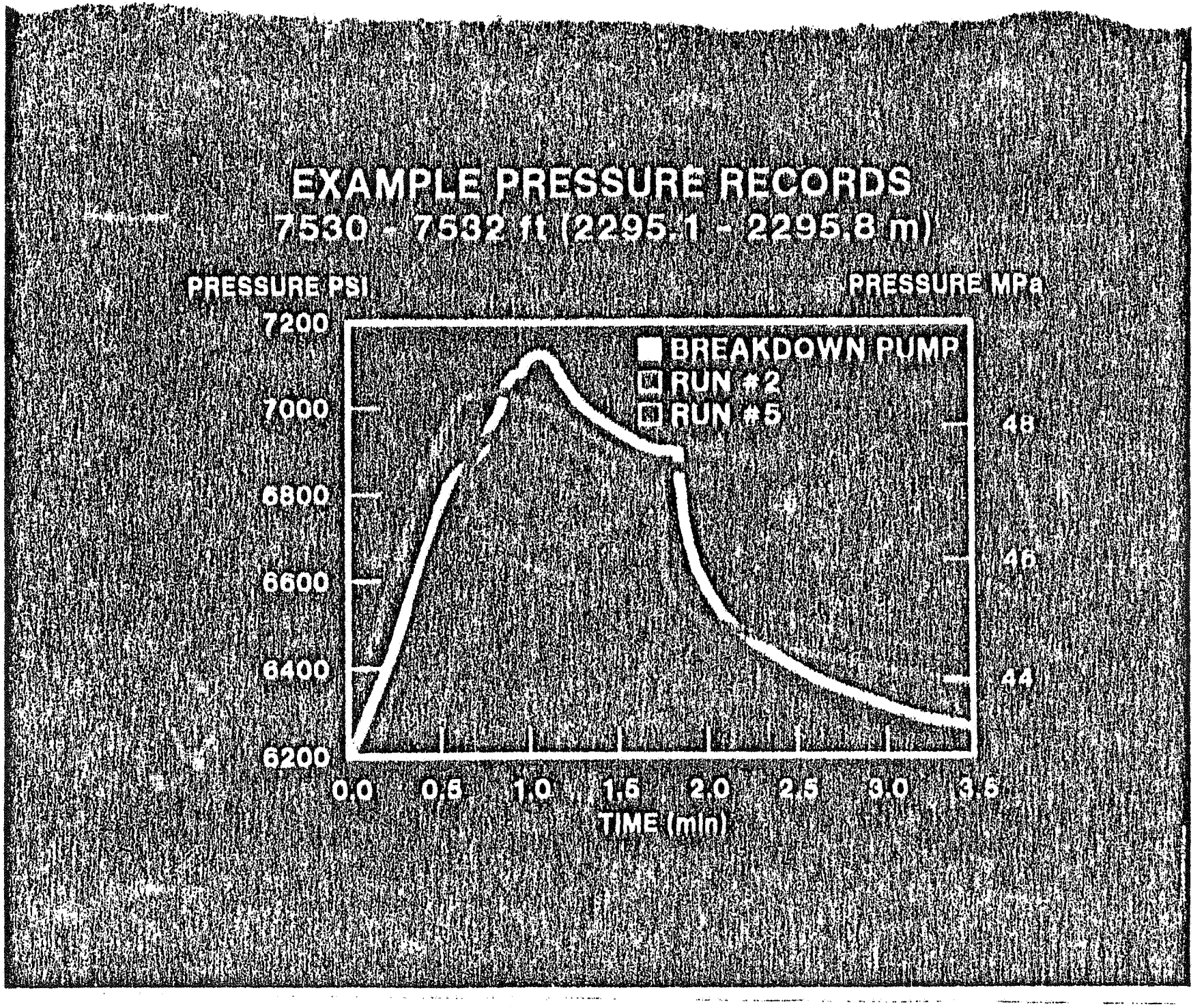
NOLTE PRESSURE DECLINE ANALYSIS

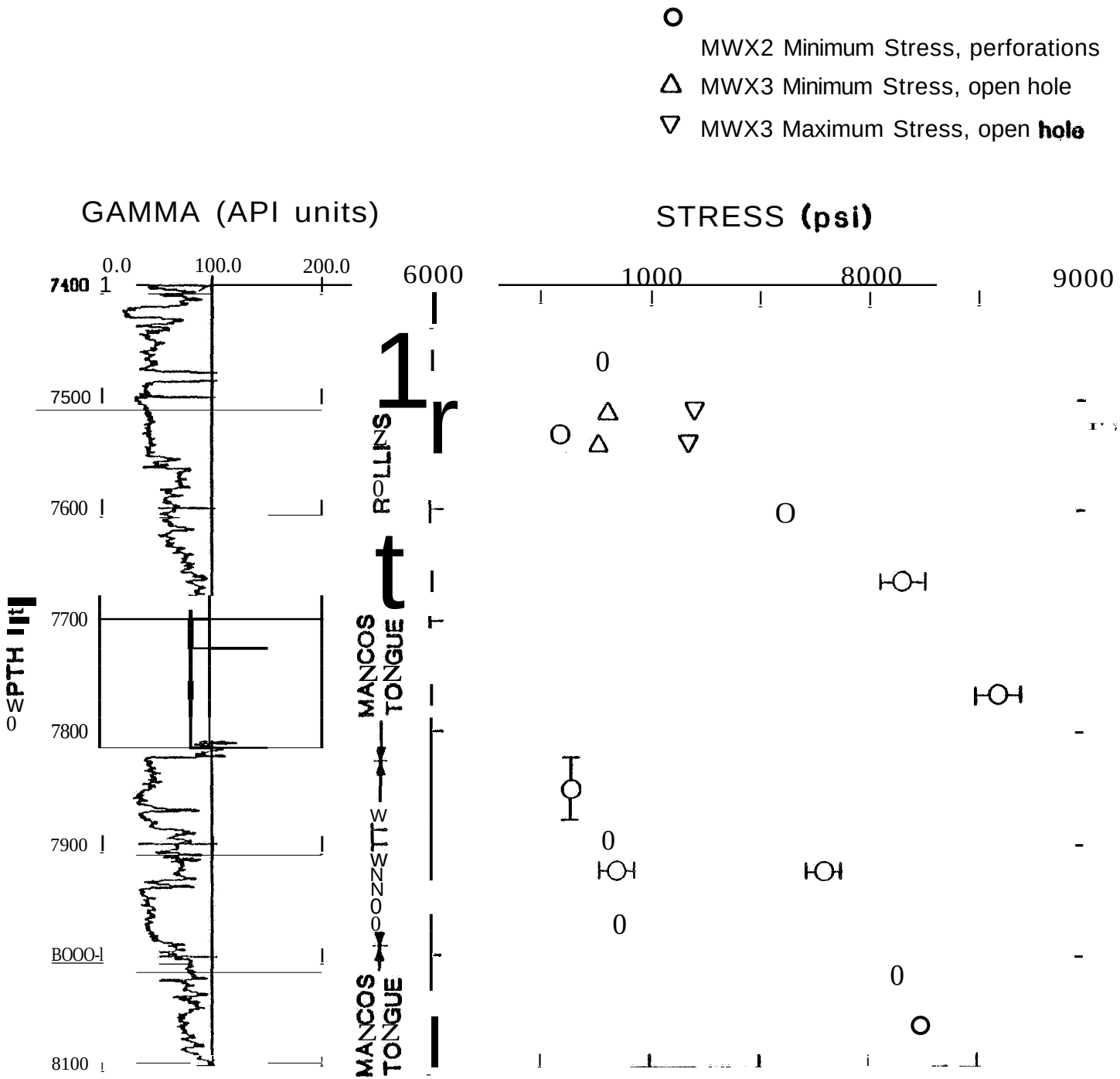
NIERODE ISIPANALYSIS

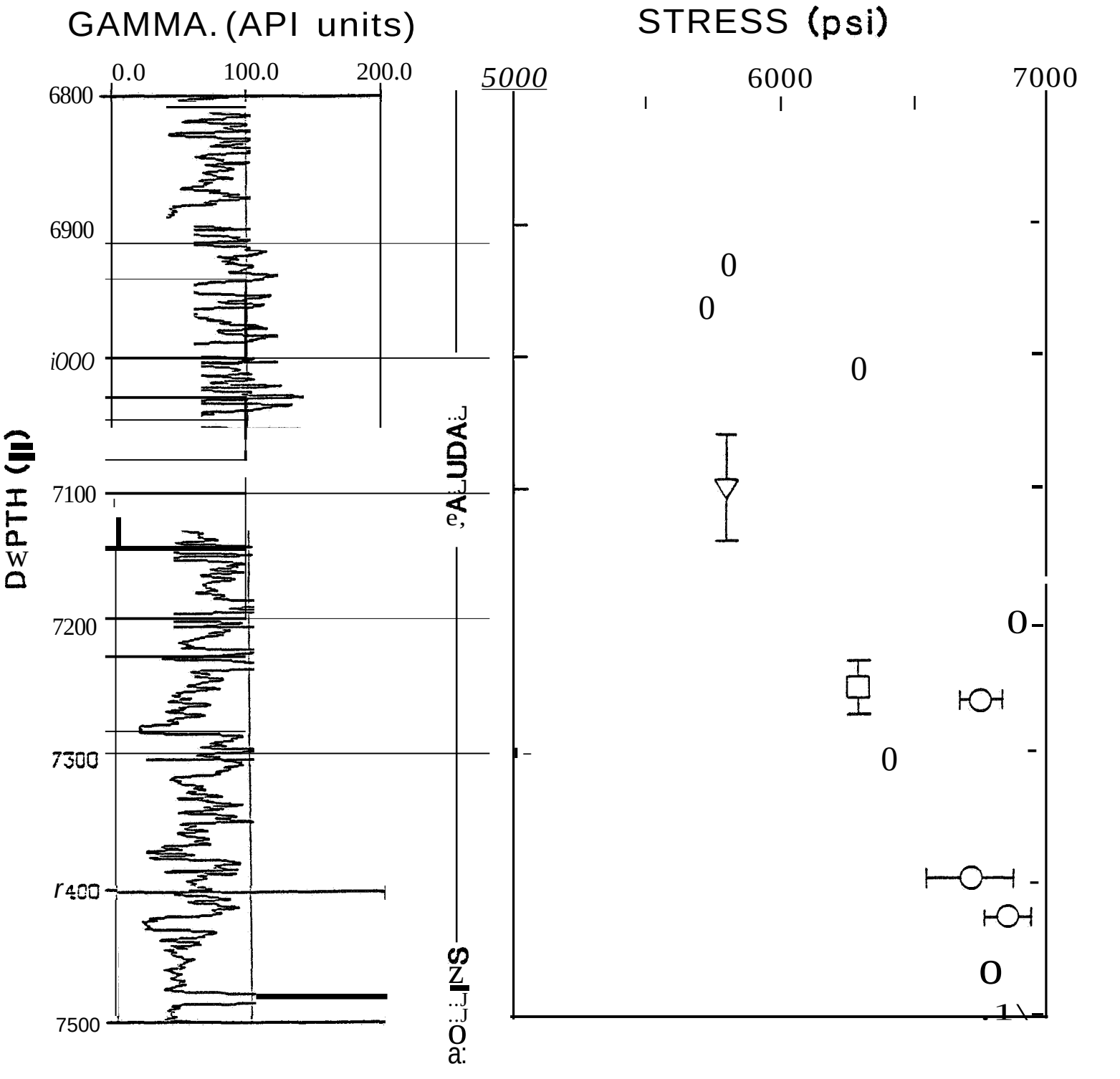
IN SITU STRESS MEASUREMENTS USING SMALL VOLUME HYDRAULIC FRACTURES




WIRELINE
2 7/8" TUBING
GRC MANDREL
H P PRESSURE GAUGE
GRC NIPPLE
PACKER
PERFORATED SUB
PERFORATIONS
RETRIEVAMATIC PACKER
2 DRILL COLLARS
FOR WEIGHT
CASING


EXAMPLE PRESSURE RECORDS
7530 - 7532 ft (2295.1 - 2295.8 m)
PRESSURE PSI
PRESSURE MPa
7200
7000
6800
6600
6400
6200
48
46
44
BREAKDOWN PUMP
RUN #2
RUN #5
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
TIME (min)


MWX2 Minimum Stress, perforations
MWX3 Minimum Stress, open hole
MWX3 Maximum Stress, open hole
GAMMA (API units)
0.0
100.0
200.0
STRESS (psi)
6000
1000
8000
9000
7400
7500
7600
7700
7800
7900
8100
ROLLINS
MANCOS TONGUE
MANCOS TONGUE

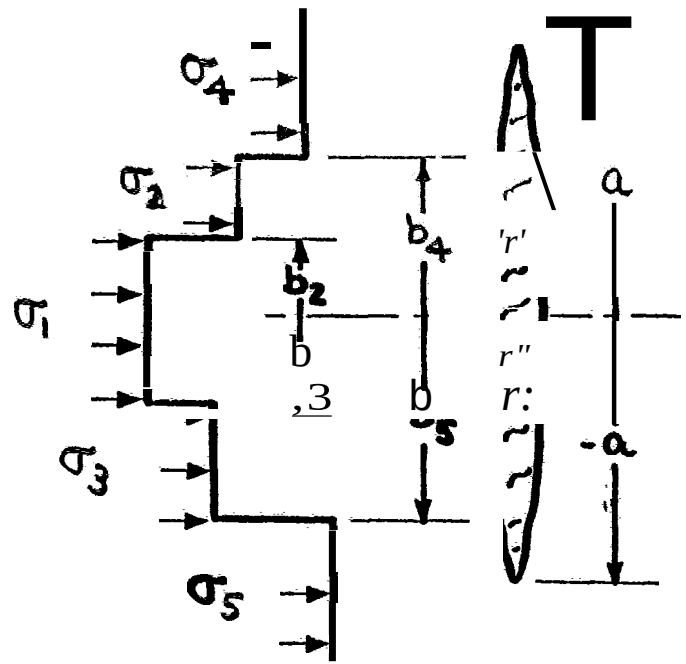

O MWX2 Minimum Stress, perforations
△ MWX3 Minimum Stress, open hole
▽ MWX3 Minimum Stress, pertoratt
O MWX1 Minimum Stress, perforations
GAMMA. (API units)
STRESS (psi)
0.0
100.0
200.0
5000
6000
7000
6800
6900
i000
7100
7200
7300
r400
7500
DEPTH (ft)

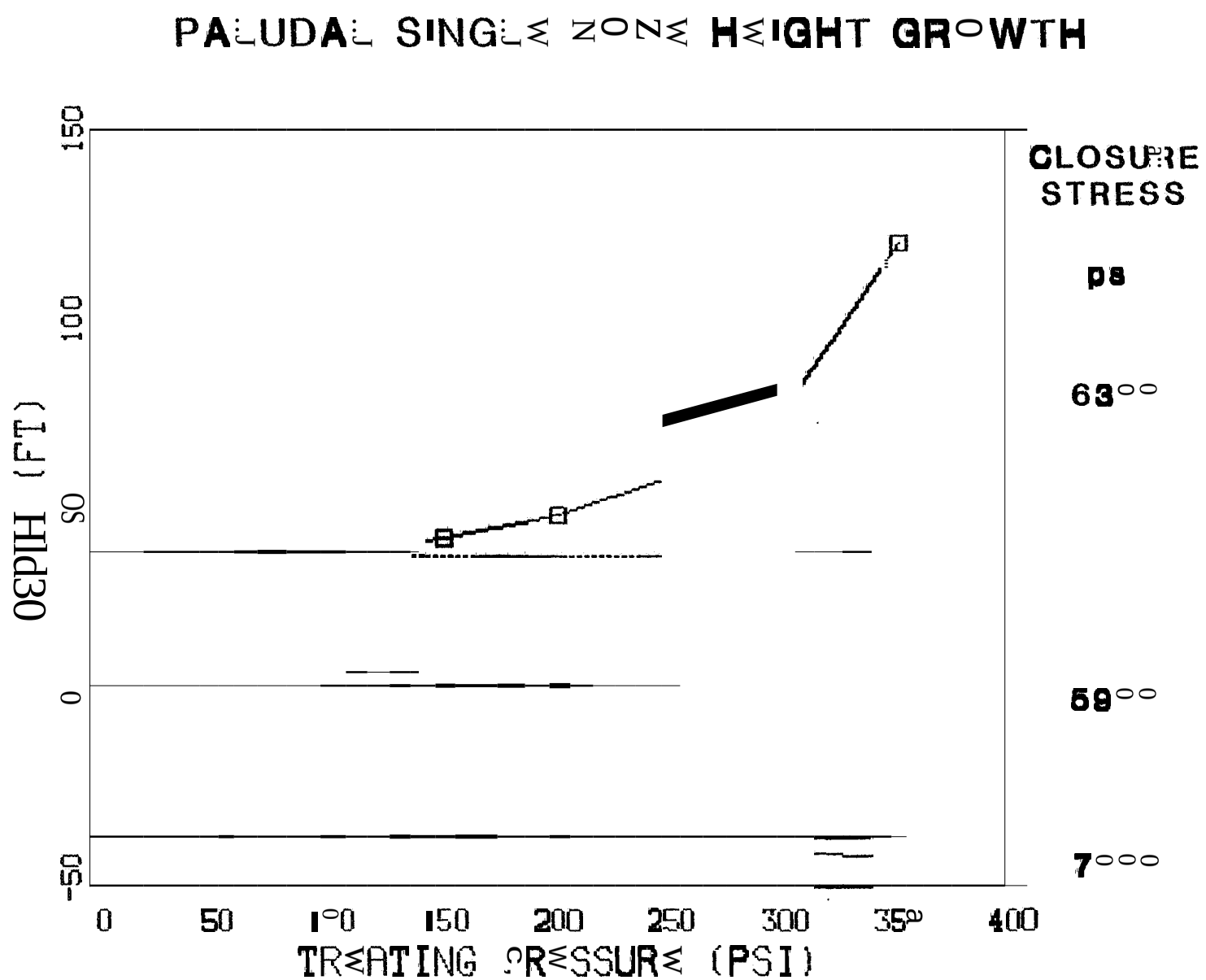
FRACTURE HEIGHT ANALYSIS

EQUILIBRIUM STRESS INTENSITY FACTOR

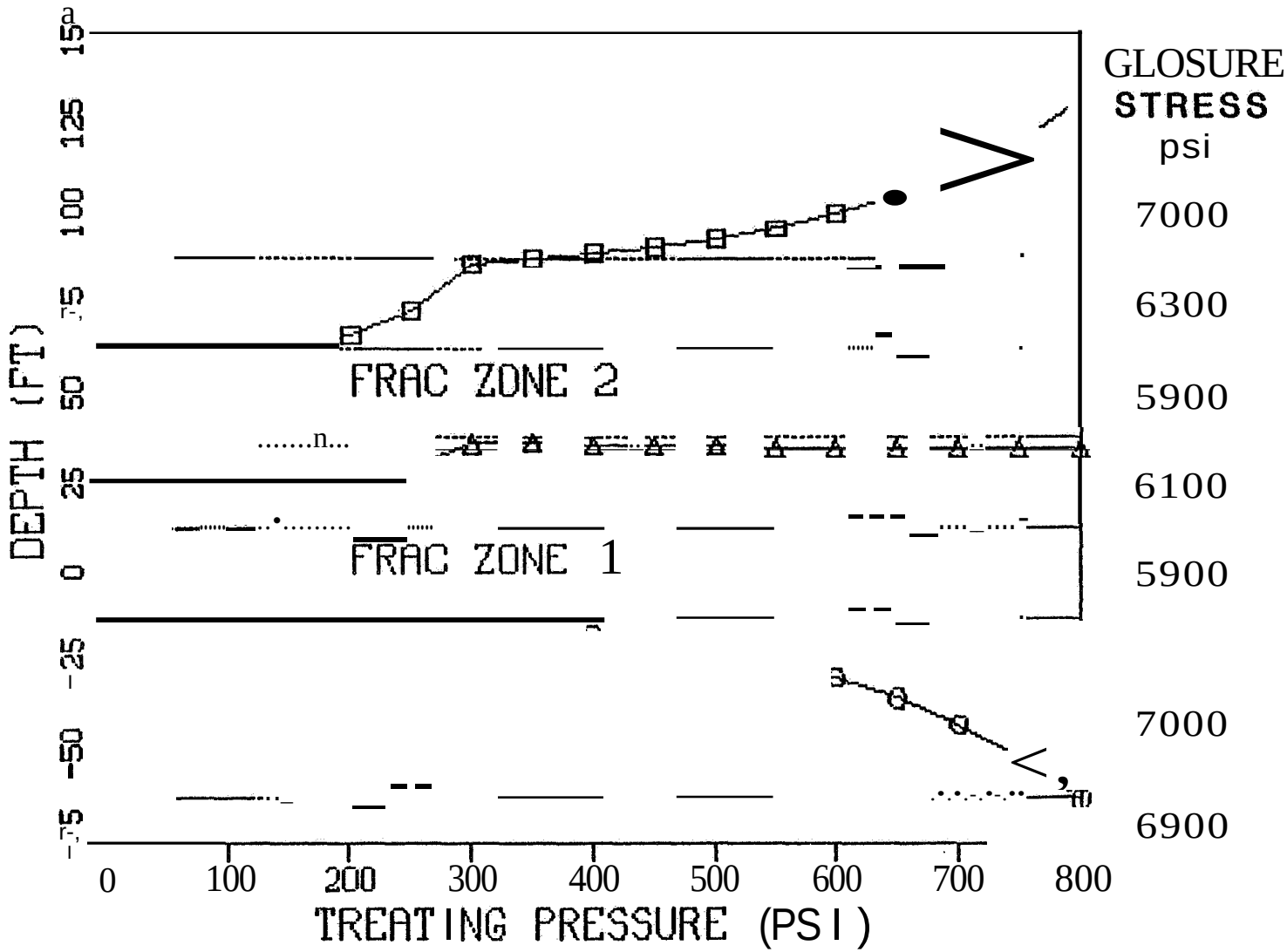
$$K_I = \frac{1}{\sqrt{\pi a}} \int_{-a}^{a} P(y) \sqrt{\frac{a+y}{a-y}}\, dy$$

$$P(y) = \begin{cases} p - \sigma_5 & -a \le y \le -b_5 \\ p - \sigma_3 & -b_5 \le y \le -b_3 \\ p - \sigma_1 & -b_3 \le y \le b_2 \\ p - \sigma_2 & b_2 \le y \le b_4 \\ p - \sigma_4 & b_4 \le y \le a \end{cases}$$




PALUDAL SINGLE ZONE HEIGHT GROWTH
CLOSURE STRESS
psi
6300
5900
7000
HID30 (FT)
150
100
50
0
-50
0
50
100
150
200
250
300
350
400
TREATING PRESSURE (PSI)

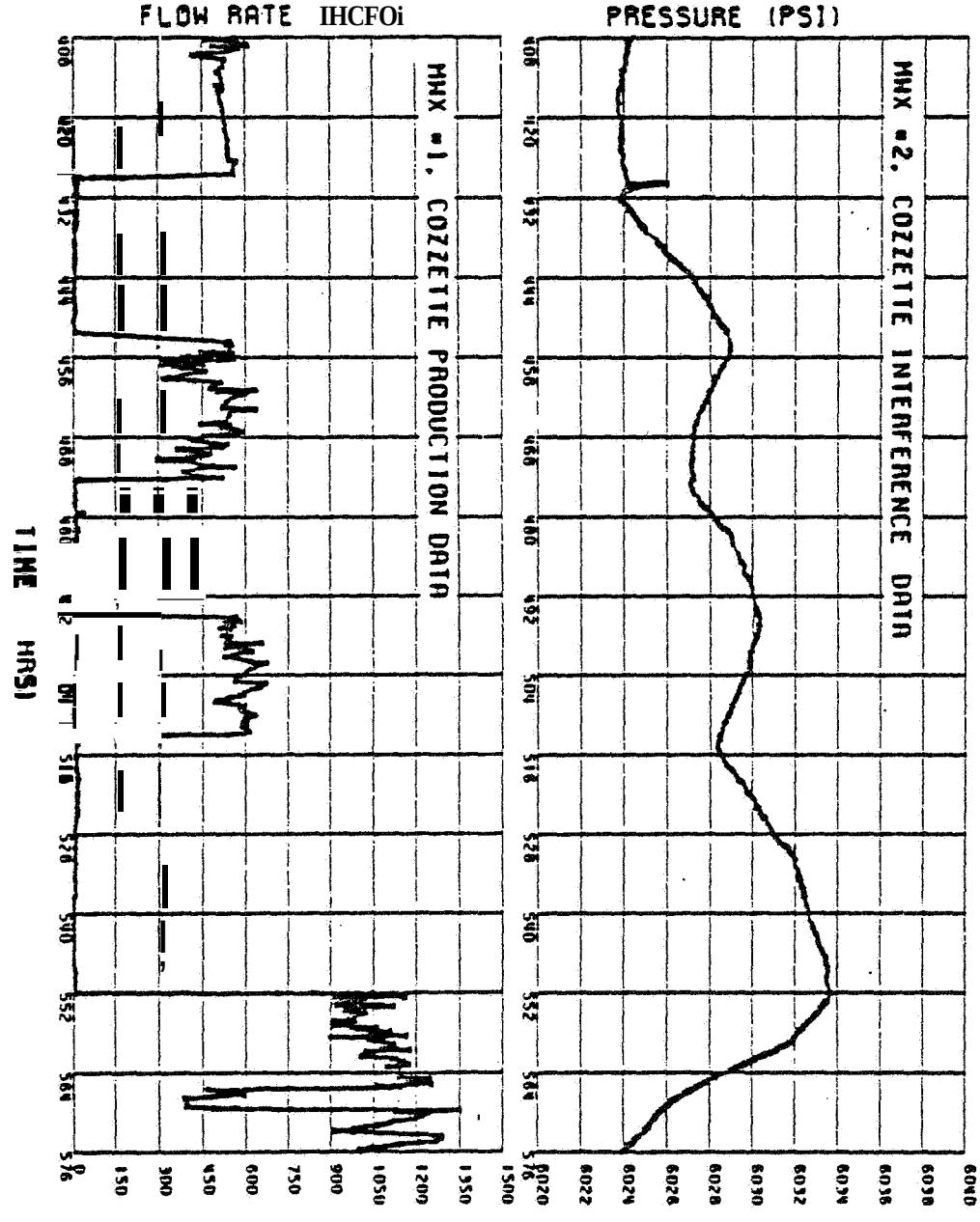
PALUDAL DUAL ZONE HEIGHT GROWTH



PALUDAL STIMULATION

OBJECTIUES:

- DETERMINE FRACTURE GEOMETRY WITH RESPECT TO RESERUOIR MORPHOLOGY
  - AZIMUTH
  - HEIGHT
  - LENGTH
  - INTERSECTION WITH LENSES
  - EFFECT OF COALS
  - EFFECT OF NATURAL FRACTURES
  - OUERALLFRACTURE BEHAUIOR
- EFFICIENTLY PRODUCE THE PALUDAL CHANNEL SANDS


PRESSURE (PSI)
MWX #2. COZZETTE INTERFERENCE DATA
FLOW RATE IHCFOi
MWX #1. COZZETTE PRODUCTION DATA
TIME HRS)

MINIFRACS

FRACTURE DIAGNOSTICS
- HEIGHT
- LENGTH
- PRESSURE
- AZIMUTH

ANALYSES FOR FRACTURE PARAMETERS
- LEAKOFF. COEFFICIENT
- EFFICIENCY
- LENGTH
- WIDTH
- CLOSURE TIME

FINE TUNE STIMULATION DESIGN

MINIFRAC TREATMENT SCHEDULES

TEST #	RATE (bpm)	UOLUME (gal)	FLUID	CONC (#/1000 gal)	PREPAD (gal)
1	10	15,000	WGA-2*	30	2100+
2	10	30,000	WGA-2*	60	4500+

* SMITH ENERGY SERVICES WATER-GELLING AGENT - 2 (NO CROSSLINKER)
+ METHANOL PREPAD FOR IMPROVED LOAD RECOVERY

PALUDAL STIMULATION PHASE I RESULTS

MINIFRAC	1	2
HEIGHT (ftl	135	150
LENGTH (ft)	275	420
C (ft/√min)	0.00129	0.0007
EFFICIENCY (%)	67	79
MAX WIDTH (in)	0.59	0.79
AUG WIDTH (in)	0.26	0.34
CLOSURE TIME (hr)	3	18
ISIP (psi)	6670	6870

FRACTURE DESIGN

SERVICE COMPANY DESIGN
- FLUIDS
- PROPPANT
- UOLUME

MWX PROJECT INPUT
- RESERUOIR AND ROCK PROPERTIES
- IN SITU STRESS AND FRACTURE HEIGHT
- FLUID/ROCK INTERACTION
- RESERUOIR GEOLOGY/MORPHOLOGY
- PROPPED LENGTH

ADDITIONAL MWXPARTICIPANTS 'INPUT

PALUDAL FRACTURE DESIGN

PROPPED LENGTH = 500 ft

HEIGHT = 200 ft

TREATING PRESSURE = 1500 psi ABOUE CLOSURE

CLOSURE TIME = 30 hr (NO PROP)

LEAKOFF COEFFICIENT = 0.0007 $ft/\sqrt{min}$

EFFICIENCY = 75% .

SAND UOLUMESUFFICIENT TO PACK BOTH FRAC ZONES IF GEL BREAKS EARLY

STIMULATION DESIGN

STAGE	FLUID (gal)	FLUID (cone)	SAND (ppg)	SAND (size)	TIME (min)
1	7700	MEOH	PREPAD		9.2
2	18000	40	PAD		21.4
3	3000	35	1.5	20/40	3.8
4	5000	35	2	20/40	6.5
5	6000	35	3	20/40	8.1
6	14000	35	4	20/40	19.7
7	18000	25	5.5	20/40	26.8
8	1000	25	5.5	12/20	1.5
9	8764	I(CI	FLUSH·		10.4
·TOTAL·	81464		193,000 Ibs		107.4

title: MWX STIMULATION ANALYSES

organization: SANDIA NATIONAL LABS

principal investigator: N.WARPINSKI

period of performance: CONTINUING

funding: PART OFMWX
APPROXIMATE 1.0 FTE RATE

STIMULATION EUALUATION

FRACTURE DIAGNOSTICS

FRACTURE ANALYSES

POST-FRAC WELL TESTING

LONG-TERM PRODUCTION

DIAGNOSTICS

BOTTOM-HOLE PRESSURE

BOTTOM-HOLE TEMPERATURE

POST-FRAC TEMPERATURE SURUEYS

POST-FRAC GAMMA SURUEYS (RA SAND)

BOREHOLE SEISMIC SYSTEM

SURFACE ELECTRIC POTENTIAL ARRAY

TILTMETER ARRAY

STIMULATION ANALYSES

NOLTE-SMITH TREATMENT· PRESSURE ANALYSIS
- FRACTURE BEHAUIOR

NIERODE ISIPANALYSIS
- LEAI(OFF COEFFrclENT

NOLTE PRESSURE DECLINE ANALYSIS
- TREATMENT PARAMETERS

FRACTURE HEIGHT
- TEMPERATURE SURUEYS
- RADIOACTIUE SAND GAMMA SURUEY
- PRESSURE/STRESS HEIGHT ANALYSIS

POST-FRACREDESIGN

FRAC PRESSURE ANALYSIS

(NOLTE AND SMITH)

FROM NORDGREN

A) LARGE FLUID LOSS

$$\Delta P = 2 \left[\frac{4E^3 \mu Q^2}{\pi^3 (1-\nu^2)^3 \, CH5} \right]^{1/4} t^{1/8}$$

B) NO FLUID LOSS

$$\Delta P = 2.5 \left[\frac{2E^4 \mu Q^2}{(1-\nu^2)^4 H^6} \right]^{1/5} t^{1/5}$$

FRAC PRESSURE ANALYSIS

(NOLTE AND SMITH)

$$\Delta P(t) \propto t^{e}$$

NEWTONIAN $1/8 < e < 1/5$

NON-NEWTONIAN $1 < e < 1$

for $n'=0.75$

$0.14 < e < 0.22$

for $n'=0.5$

$0.17 < e < 0.25$

FRAC PRESSURE ANALYSIS

(NOLTE AND SMITH)

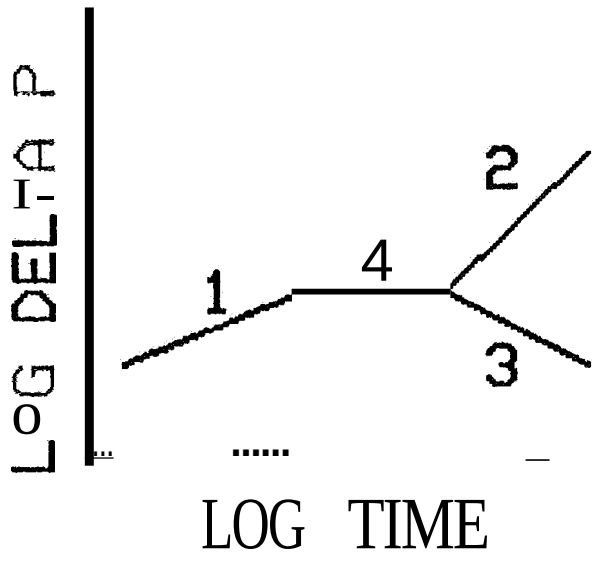
FOUR TYPICAL CASES

1) SMALL, CONSTANT SLOPE
   NO HEIGHT GROWTH

2) UNIT SLOPE
   SCREENOUT

3) NEGATIUE SLOPE
   HEIGHT GROWTH

4) ZERO SLOPE
   HEIGHT GROWTH
   INCREASED LEAKOFF



NIERODE ANALYSIS

SEMI-EMPIRICAL THEORY TO EUALUATE
THE LEAKOFF COEFICIENTFROM THE
CHANGE IN THE APPARENT CLOSURE STRESS

$$FG(t_Z) = FG(t_1)\,[1 + A(C\sqrt{t_2} - \sqrt{t_1})B]$$

A=0.20233
8=0.47850

REQUIRES MULTIPLE SHUT-INS DURING **THE**
TREATMENT TO EUALUATE THE CHANGE **IN**
THE ISIP

NOLTE ANALYSIS

ESTIMATE FRACTURE PARAMETERS FROM THE PRESSURE DECLINE BEHAUIOR AFTER SHUT IN

$$\frac{dP(\delta)}{dT} = \frac{4CH_p E'}{H^2 B_s \pi \sqrt{t_o}} f(\delta)$$

$$2(\sqrt{1+\delta} - \sqrt{\delta}) > f(\delta) > \sin^{-1} t\,ri-\delta)^{-1/2}]$$

δ - DIMENSIONLESS TIME
C - LEAKOFF COEFFICIENT
H_p - LEAKOFF HEIGHT
E' - WEIGHTED MODULUS
H - TOTAL HEIGHT
Bs-PRESSURE RATIO
to- PUMP TIME

NOLTE ANALYSIS

USE THE ACTUAL DECLINE PRESSURE IN A CURUEMATCHING TECHNIQUE TO DEFINE THE MATCH PRESSURE

$$P^* = \frac{C H_p E' \sqrt{t_o}}{H^2 B_s}$$

H_p FROM LOGS
H FROM TEMPERATURE LOGS/DIAGNOSTICS
B_s FROM FLUID PROPERTIES
to IS THE PUMP TIME
E' FROM CORE/LOGS/EXPERIENCE

CALCULATE C) THE LEAKOFF COEFFICIENT

NOLTE ANALYSIS

ONCE FLUID LOSS COEFFICIENT IS KNOWN

$$L = \frac{Q t_o}{\pi C H_p \sqrt{t_o}\,(1+\rho)}$$

WHERE $\rho = f(\delta) \cdot g(P(\phi))$

ADDITIONALLY,

$$E_{fn} = \frac{\rho}{1+\rho}$$

AND

$$\bar{w} = \pi C \frac{H_p}{H} \sqrt{t_o}\, \rho$$

POST-FRACPRESSURE/STRESS HEIGHT ANALYSIS

ESTIMATE FRACHEIGHTFROMMEASURED BOTTOM-HOLE TREATMENT PRESSURE

REQUIRES:

IN SITU STRESS DISTRIBUTION
BOTTOM-HOLE PRESSURE US TIME

" ADDITIONAL STRESS TESTS REQUIRED?

DO RESULTS MATCH WITH FRAC MODEL?

ºALUDAL RESULTS

EXAMPLES:

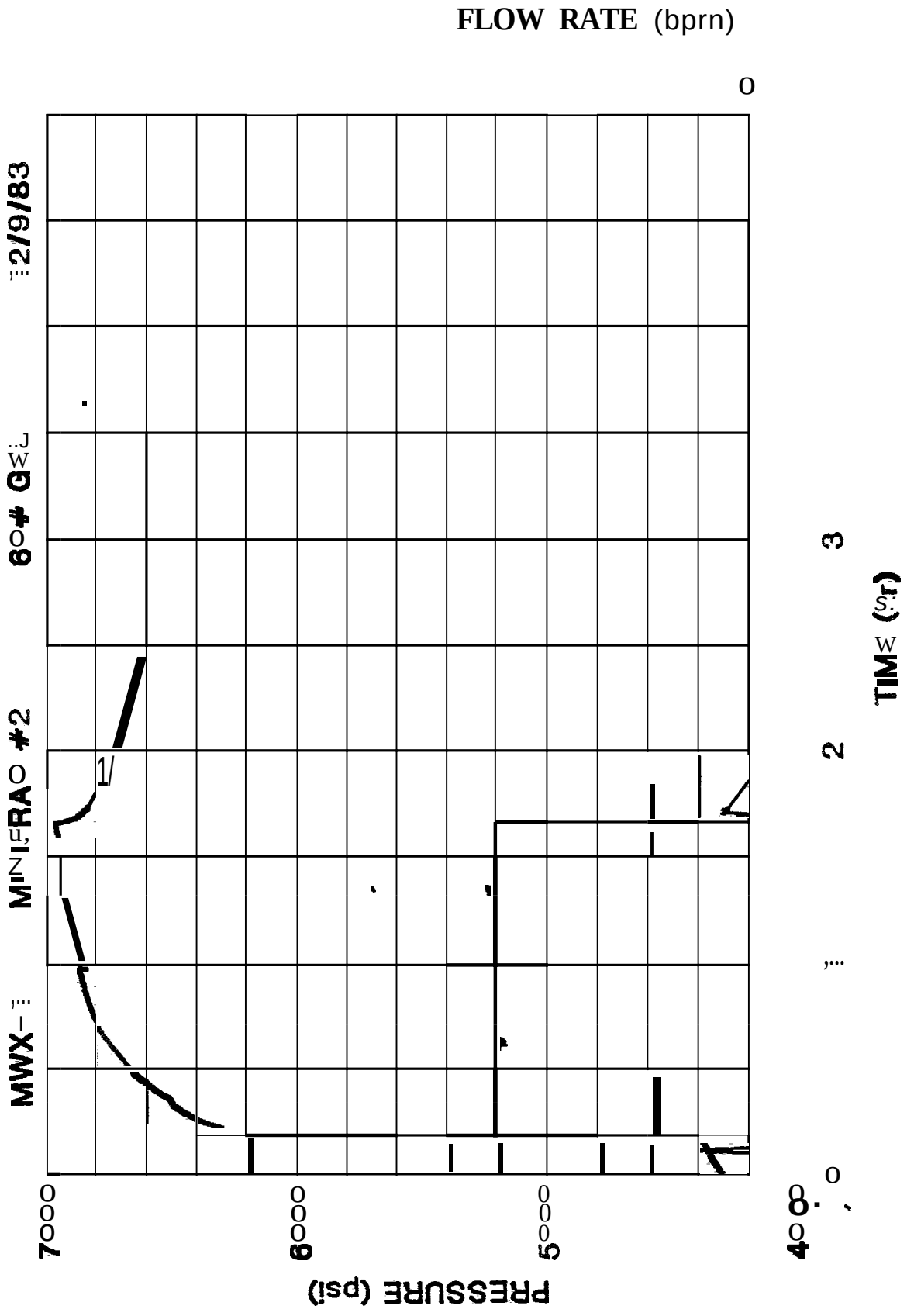
MINIFRAC #2

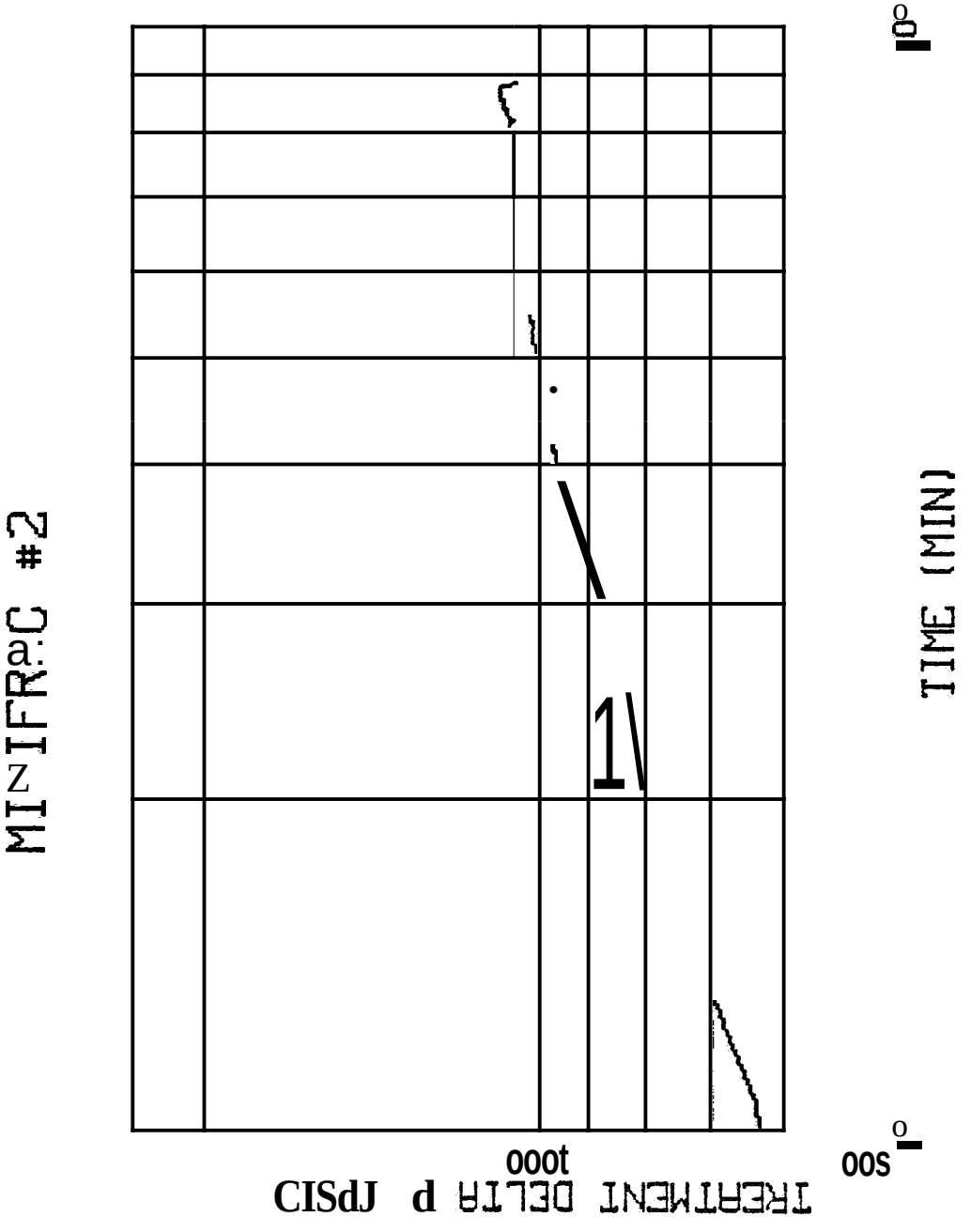
STIMULATIºN

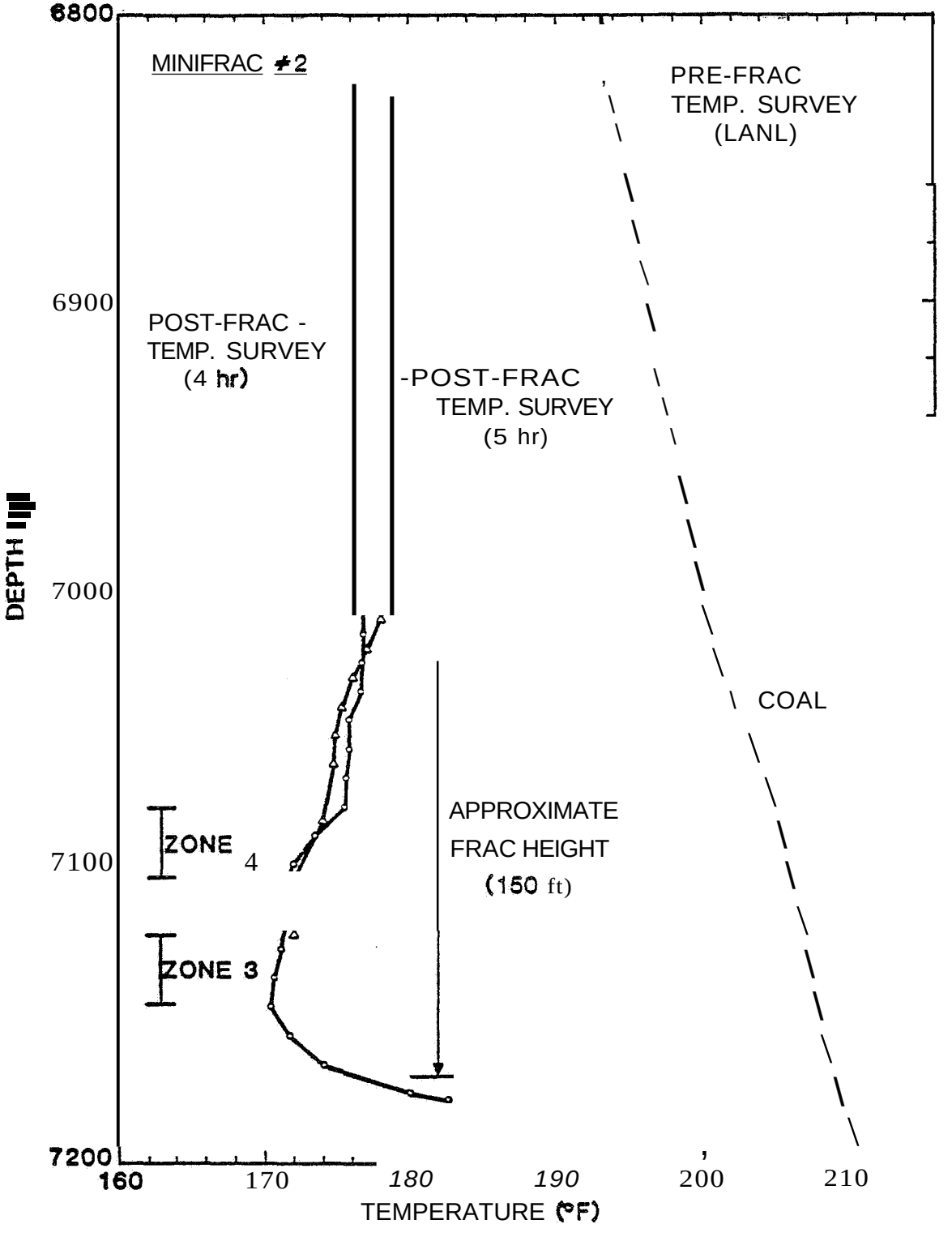
MINIFRAC TREATMENT SCHEDULES

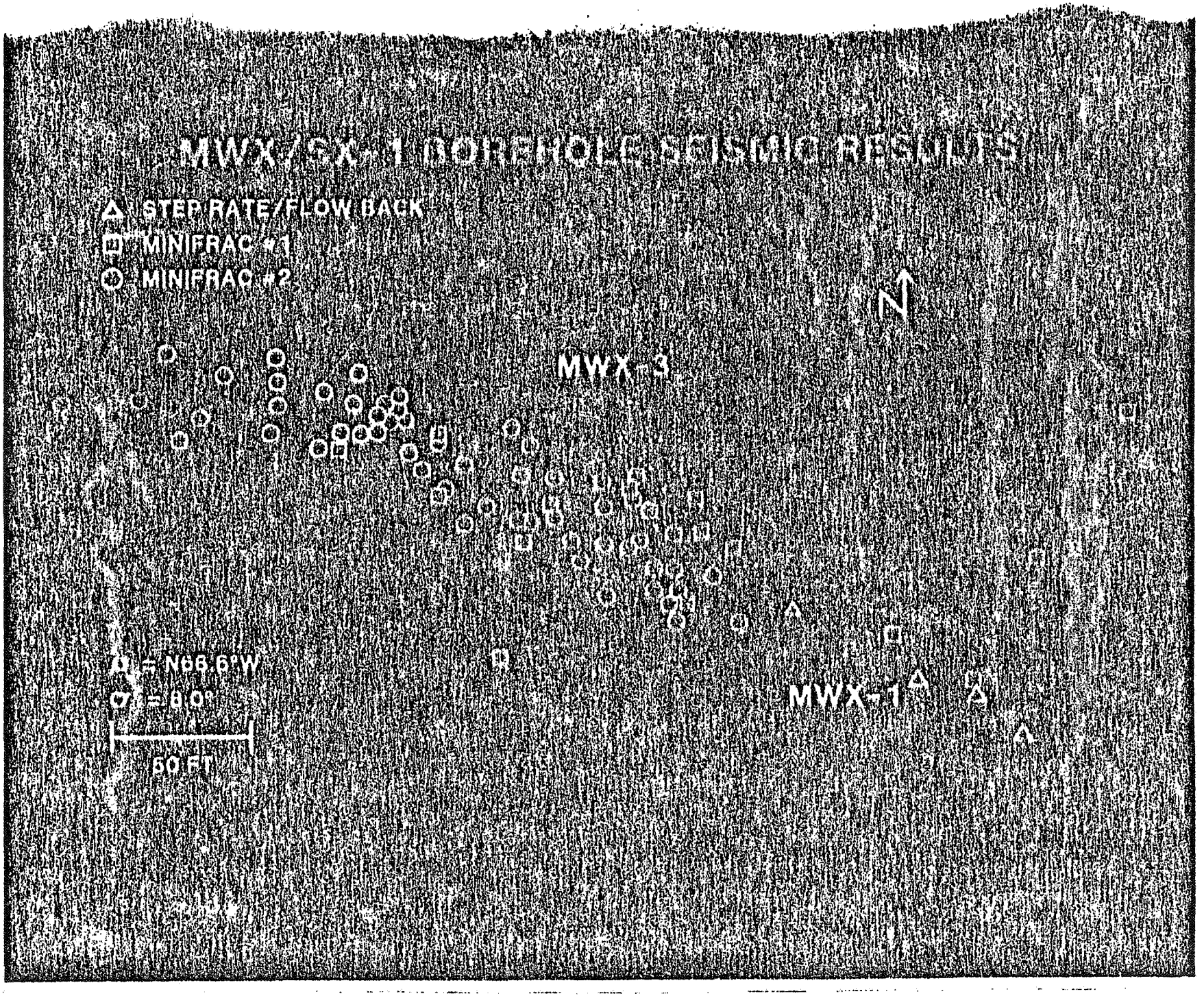
TEST #	RATE (bpm)	UOLUME (ga1)	FLUID	CONe (#/1000 gal)	PREPAD (gal)
1	10	15,000	WGA-2*	30	2100+
2	10	30,000	WGA-2*	60	4500+

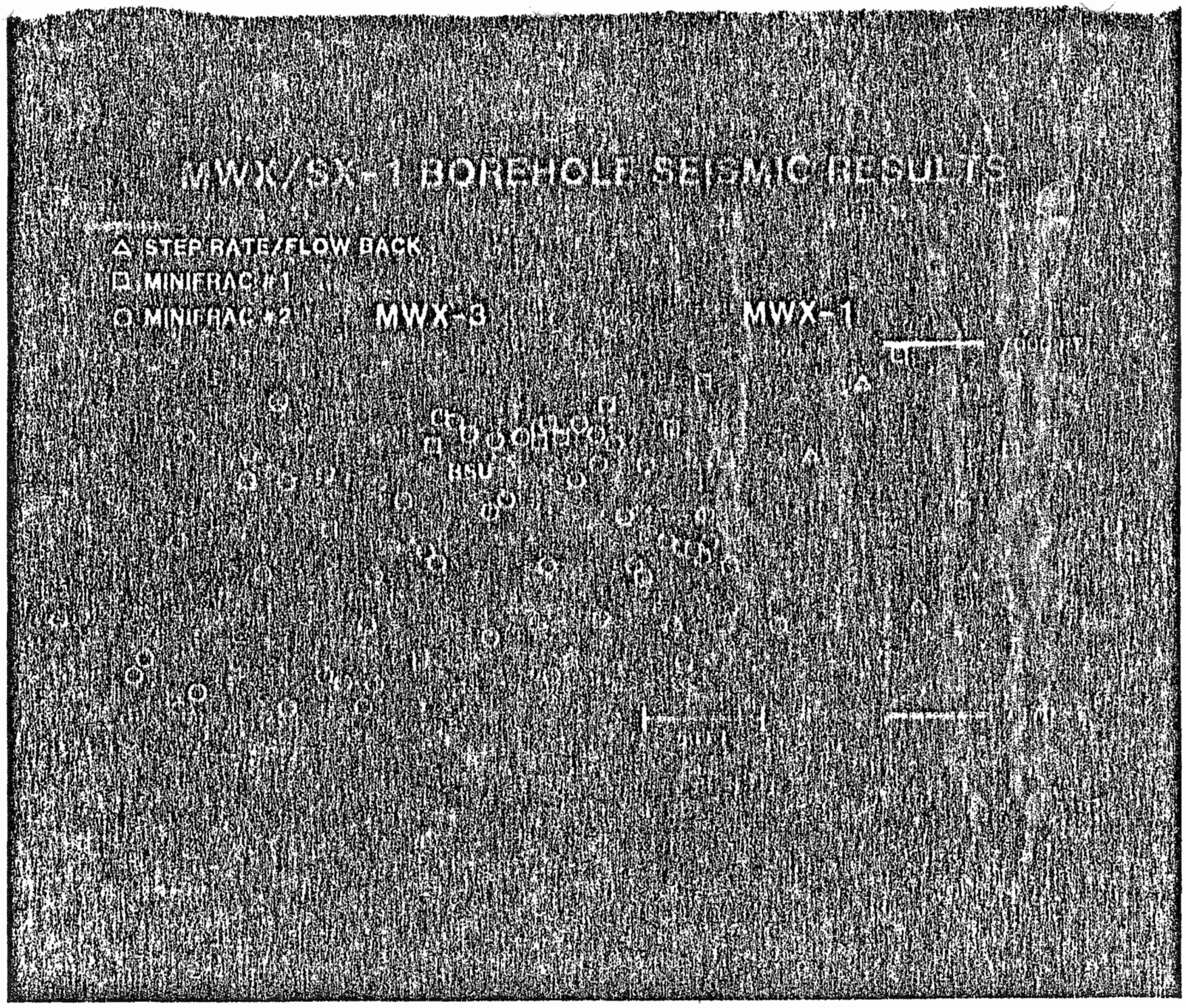
* SMITH ENERGY SERVICES WATER-GELLING AGENT - 2 (NO CROSSLINKER)
\+ METHANOL PREPAD FOR IMPROVED LOAD RECOVERY

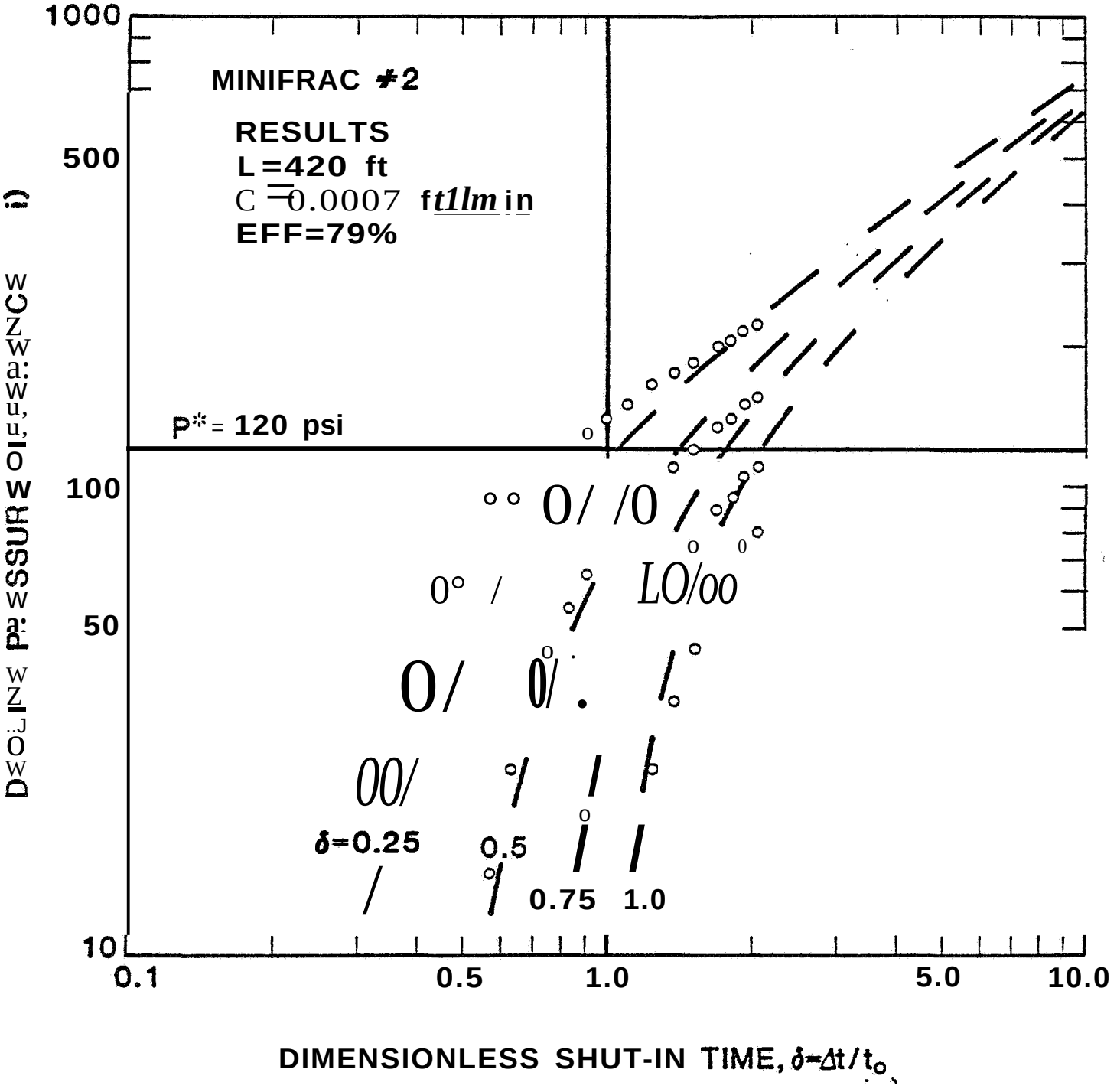

FLOW RATE (bprn)
PRESSURE (psi)
TIME (hr)
MWX
MINERAL #2
60# GEL
2/9/83
7000
6000
5000
4000
0
2
3


MI IFRa:C #2
TIME (MIN)
0
500
0
1000
TREATMENT DELTA p CISdJ


MINIFRAC #2
PRE-FRAC
TEMP. SURVEY
(LANL)
POST-FRAC -
TEMP. SURVEY
(4 hr)
-POST-FRAC
TEMP. SURVEY
(5 hr)
COAL
APPROXIMATE
FRAC HEIGHT
(150 ft)
ZONE 4
ZONE 3
DEPTH
6800
6900
7000
7100
7200
160
170
180
190
200
210
TEMPERATURE (°F)


MWX/GX-1 BOREHOLE SEISMIC RESULTS
STEP RATE/FLOW BACK
MINIFRAC #1
MINIFRAC #2
N
MWX-3
MWX-1
A = N66.6°W
σ = 8.0°
50 FT


MWX/SX-1 BOREHOLE SEISMIC RESULTS
△ STEP RATE/FLOW BACK
□ MINIFRAC #1
○ MINIFRAC #2
MWX-3
MWX-1


MINIFRAC #2
RESULTS
L=420 ft
C=0.0007 ft/lm in
EFF=79%
P* = 120 psi
δ=0.25
0.5
0.75
1.0
1000
500
100
50
10
0.1
0.5
1.0
5.0
10.0
DIMENSIONLESS SHUT-IN TIME, δ=Δt/t

RESULTS OF PHASE I TESTS

CLOSURE STRESS = 5900 psi

. LOWLEAKOFF

NO APPARENT EXTENSIUE HEIGHT GROWTH
HEIGHT = 150 ft

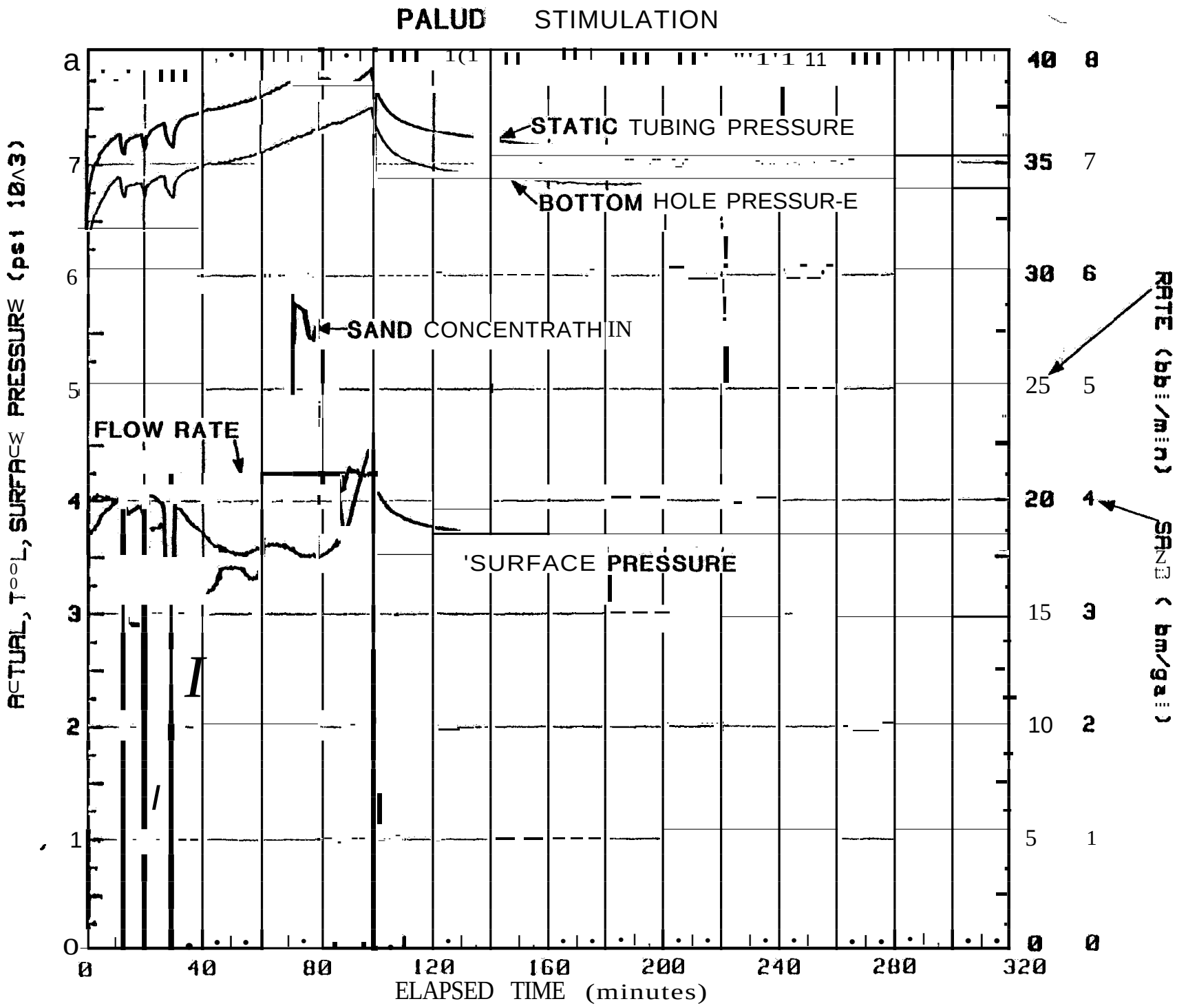
FRACTURE ORIENTATION = N65W

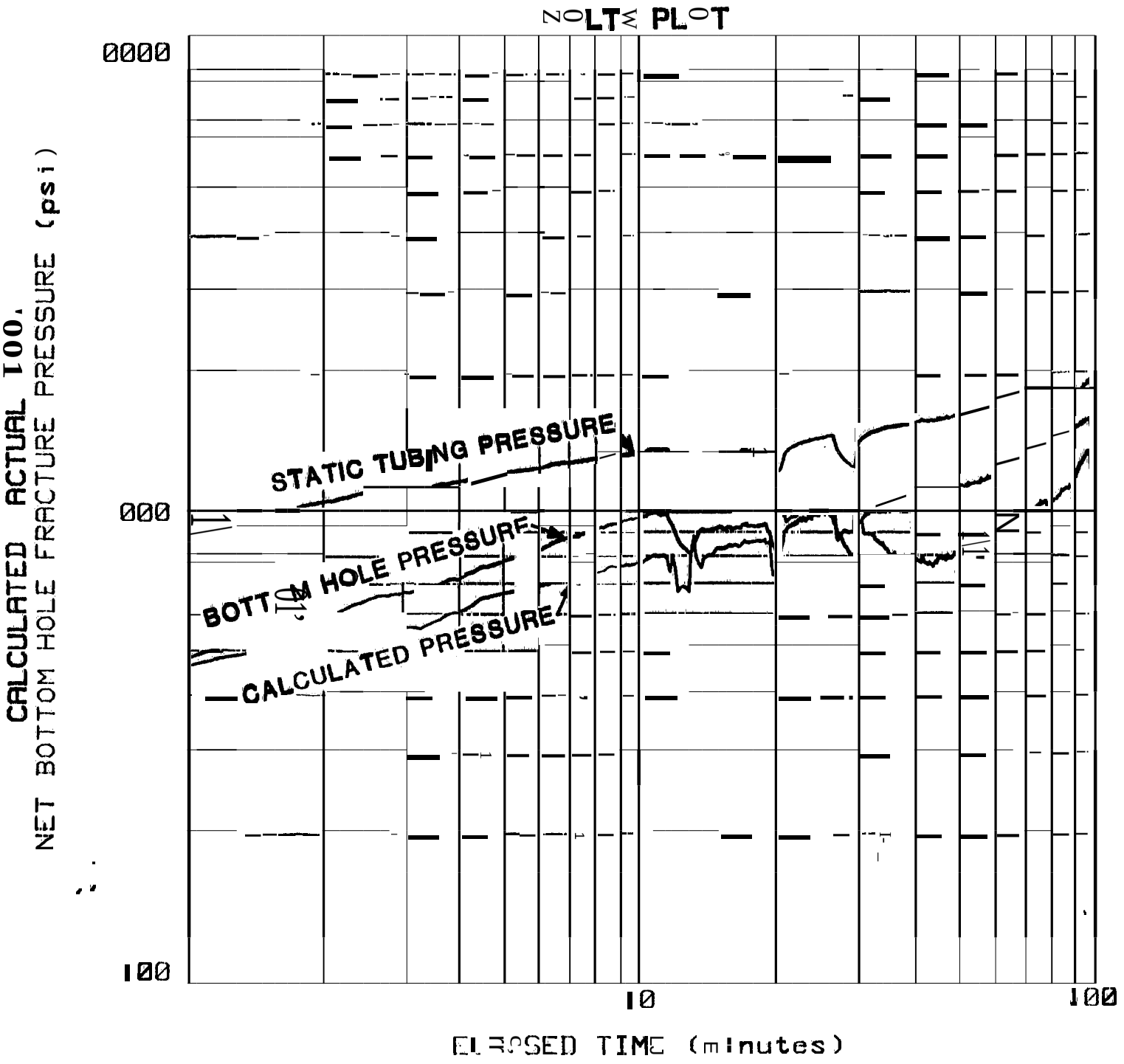
ADEQUATE LENGTH GROWTH

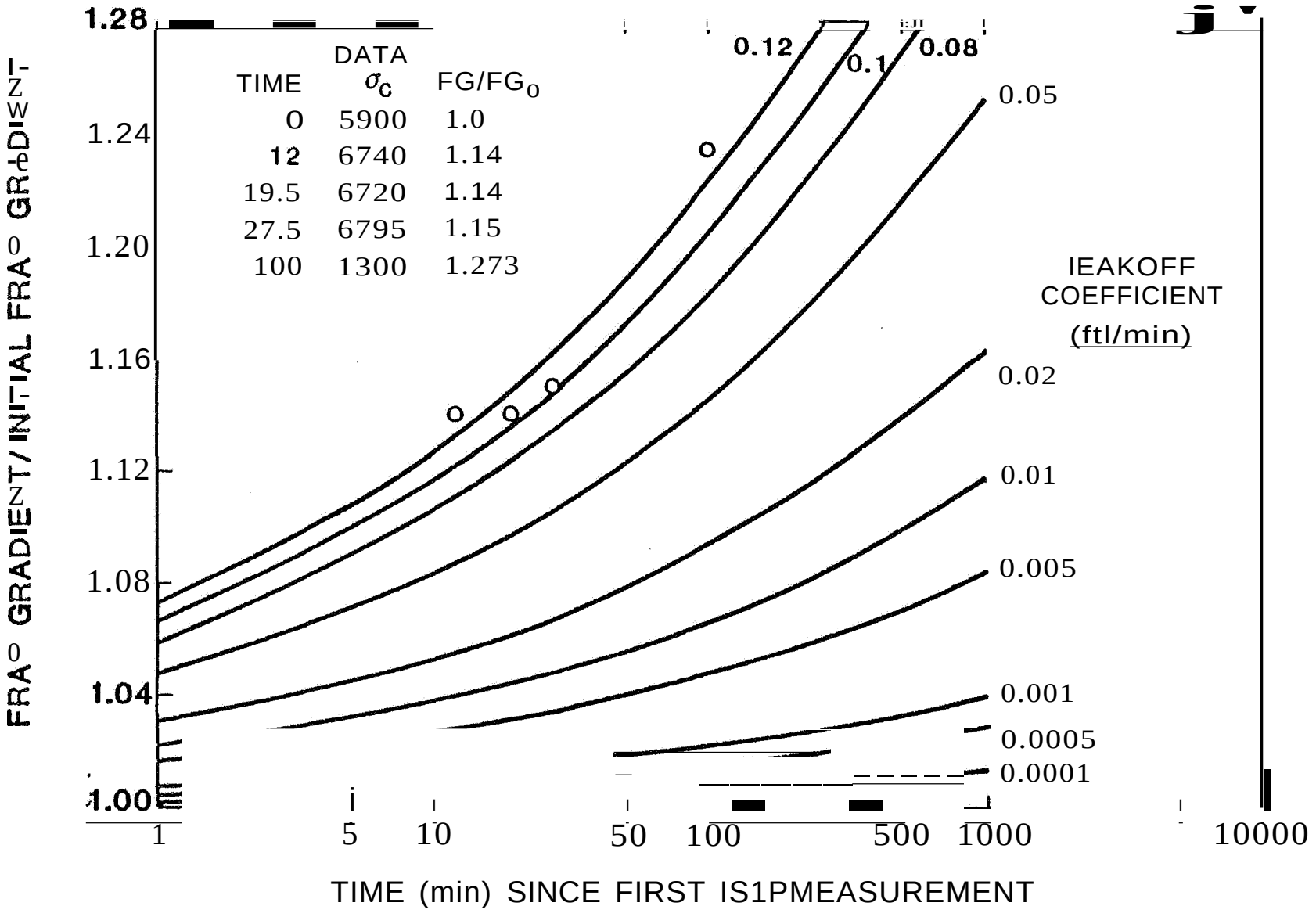
HIGH INJECTION PRESSURES
HIGH STRESS REGIONS ABOUEOR BELOW
FRACTURE BRANCHING

HYDRAULIC FRACTURE STIMULATION DESIGN

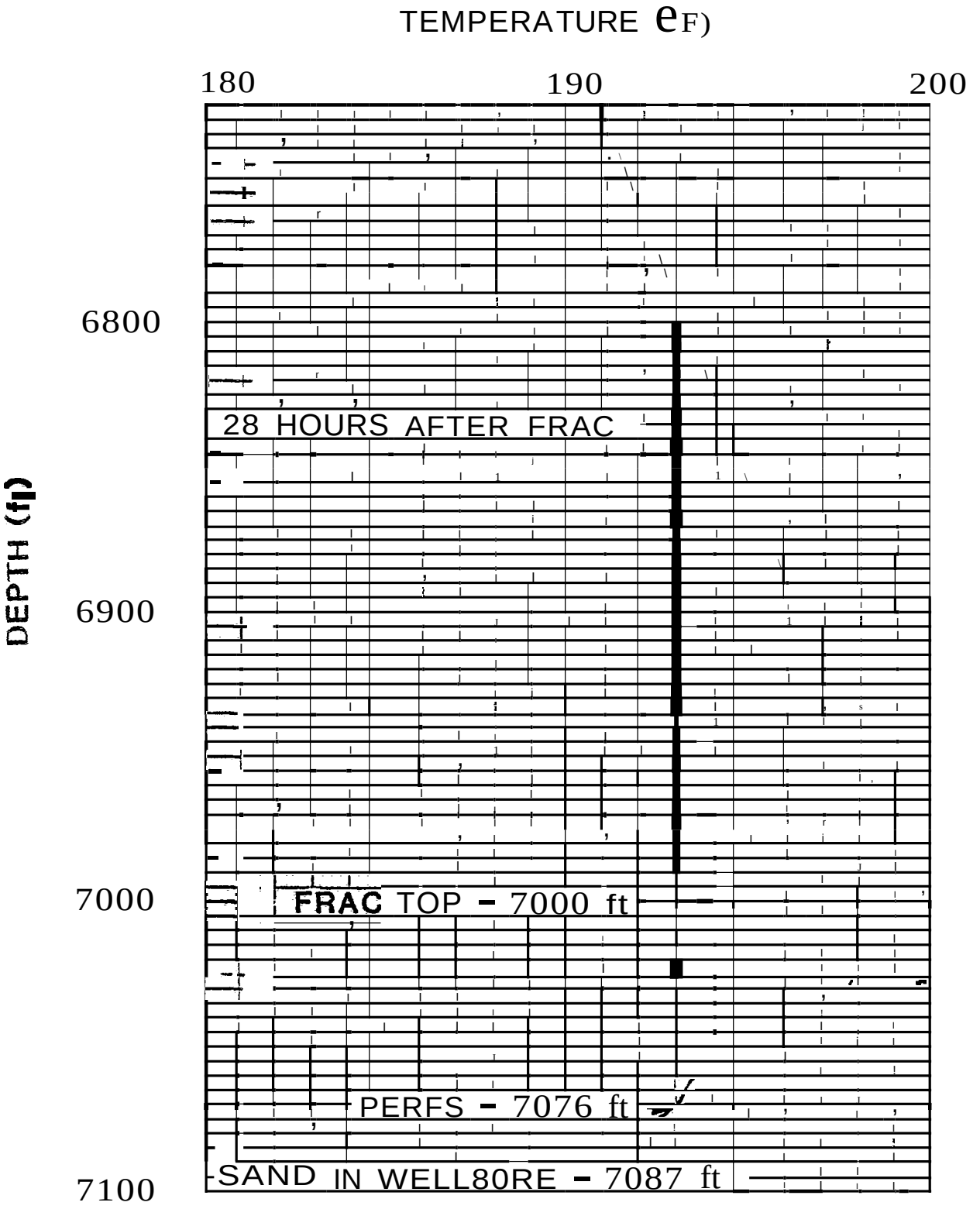
PROPPED LENGTH	500 ft	
FLUID LENGTH	600 ft	
ESTIMATED HEIGHT ----	200 ft	
LEAKOFF COEFFICIENT -	0.00065	$\frac{ft}{\sqrt{min}}$

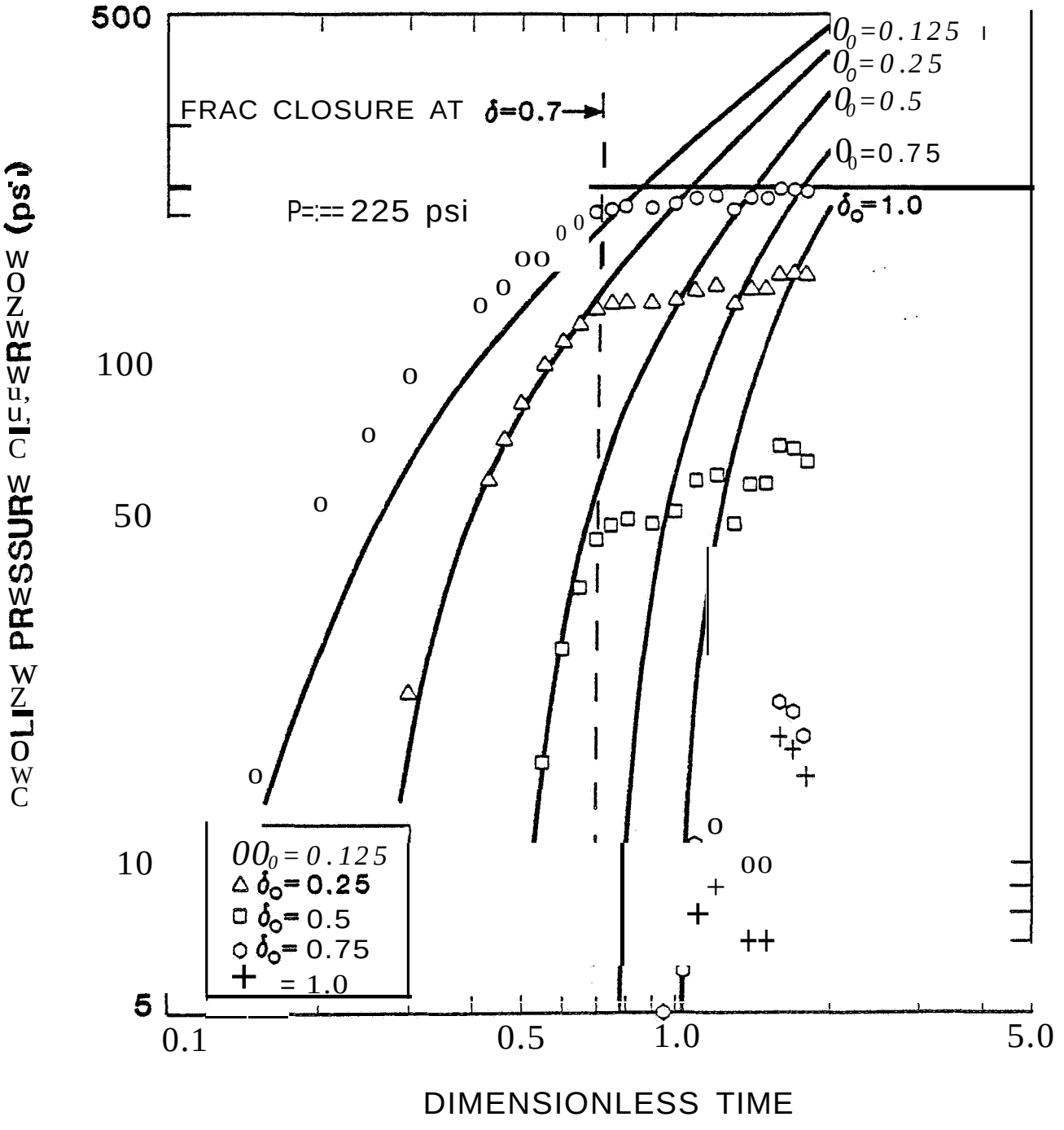

PALUD STIMULATION
STATIC TUBING PRESSURE
BOTTOM HOLE PRESSUR-E
SAND CONCENTRATH IN
FLOW RATE
'SURFACE PRESSURE
ACTUAL, TOOL, SURFACE PRESSURE (psi 10^3)
RATE (bbl/min)
SAND (lb/gal)
ELAPSED TIME (minutes)
0
40
80
120
160
200
240
280
320
1
2
3
4
5
6
7
8
10
15
20
25
30
35


NOLTE PLOT
CALCULATED ACTUAL 100.
NET BOTTOM HOLE FRACTURE PRESSURE (psi)
0000
000
100
STATIC TUBING PRESSURE
BOTTOM HOLE PRESSURE
CALCULATED PRESSURE
10
100
ELAPSED TIME (minutes)


FRAC GRADIENT/INITIAL FRAC GRADIENT
1.28
1.24
1.20
1.16
1.12
1.08
1.04
1.00
DATA
TIME σc FG/FGo
0 5900 1.0
12 6740 1.14
19.5 6720 1.14
27.5 6795 1.15
100 1300 1.273
0.12
0.1
0.08
0.05
0.02
0.01
0.005
0.001
0.0005
0.0001
LEAKOFF COEFFICIENT (ftl/min)
1
5
10
50
100
500
1000
10000
TIME (min) SINCE FIRST IS1PMEASUREMENT

PALUDAL POST-FRAC TEMPERATURE LOG




500
100
50
10
5
0.1
0.5
1.0
5.0
DIMENSIONLESS TIME
FRAC CLOSURE AT δ=0.7
P=225 psi
δ0=0.125
δ0=0.25
δ0=0.5
δ0=0.75
δ0=1.0
δ0=0.125
δ0=0.25
δ0=0.5
δ0=0.75
= 1.0

PALUDAL STIMULATION . NOLTE ANALYSIS RESULTS

HEIGHT Cft)	200	180
NETLEAKOFF C_W (ft/√min)	.0015	.0012
GROSS LEAKOFF C_W (ft/√min)	.0006	.00053
WING LENGTH Cft)	400	400
AUERAGE WIDTH (in)	0.7	0.78
EFFICIENCY C%)	76.	76

PALUDAL STIMULATION RESULTS

TREATMENT PRESSURE ANALYSIS
- NO EXCESSIUE HEIGHT GROWTH
- GREATER THAN EXPECTED EXPONENT

ISIPANALYSIS
- NOT APPLICABLE IN THIS FORMATION

PRESSURE DECLINE ANALYSIS
- LENGTH SOMEWHAT LESS THAN DESIGN
- GOOD FLUID EFFICIENCY
- CLOSURE AT 70 min

PRESSURE/STRESS ANALYSIS
- ABNORMAL TREATMENT PRESSURE
- "ADDITIONAL STRESS TESTS REOUIRED

STIMULATION ANALYSES
CONCLUSIONS

STIMULATION ANALYSES, TOGETHER WITH FRACTURE DIAGNOSTICS) CANPROUIDE VALUABLE INFORMATION 0N FRACTURE BEHAVIOR

FRACTURE DIAGNOSTICS

ORGANIZATION:	SANDIA NATIONAL LABORATORIES
PRINCIPAL INVESTIGATOR:	DENNIS ENGI
PERIOD OF PERFORMANCE:	CONTINUING
CONTRACT OR PROJECT FUNDING:	PART OF MWX AT AN APPROXIMATE 3.0 FTE RATE

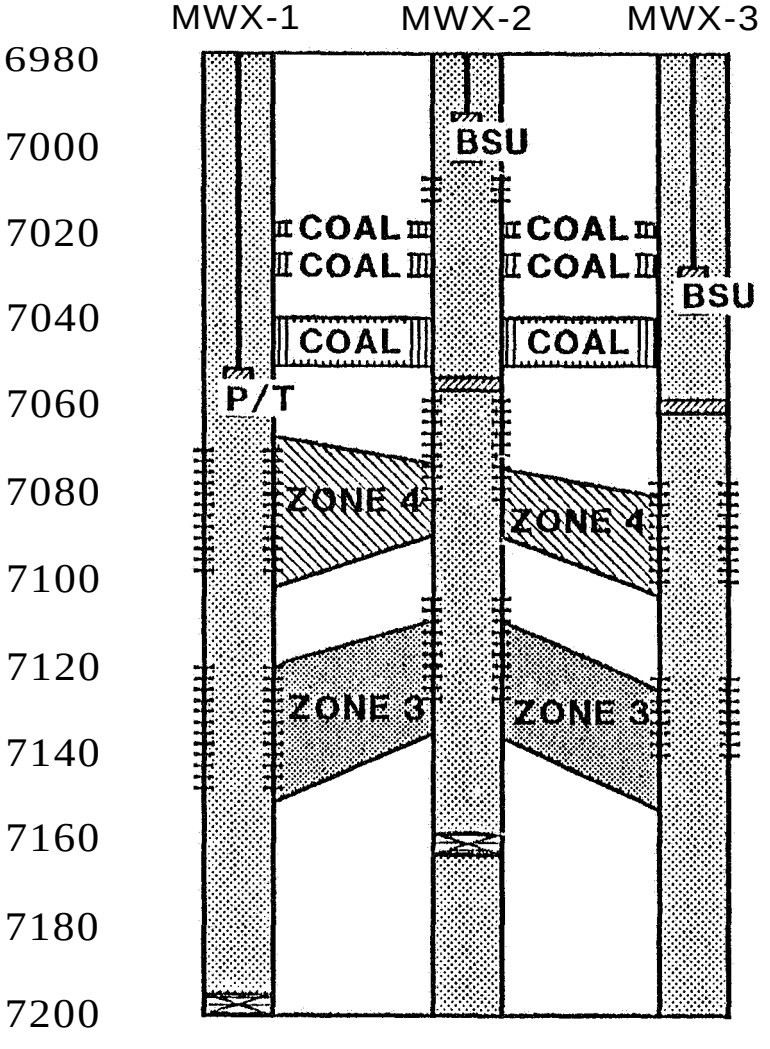
INDUSTRY ASSESSMENT OF SELECTED TIGHT GAS R&D OBJECTIVES

R&D OBJECTIVES	RANK ORDER: Importance to Company 11	Importance to Industry 11	level 01 Ellort 11	Time to Achleve 21	RISK OF R&D FAILURE 31 (Low / Med / High)	LEVEL OF PAYOFF	COMMENTS·,
1. PREDICT ANDIOR CONTROL fRACTURE GEOMETRY jSHAPE, EXTENSION, AND ORIENTATION)				" 7		Low Med High	I. First priority due 10 consensus o' high payoff; generally, prediction lo",e. risk elld .oone., conl.oll. highe-•nd lonoe. le.m.
2. MEASURE IN SITU STRESS TO BETTER PREDICT FRACTURE GEOMETRY	3	2	2	4		Low Med HIOh	2. Necessary 10. p"dlCllloniconl,ol-.I.k, timing .nd payoff 'evo.able
3. PENETRATE LENSES REMOTE FROM THE WELLBORE	9	8	8	9		low Med High	3. Risks 100 high .elallve 10 payoll-Ianllcula, resource and technology 0•• ecovering II ,-- In the 'UIU'8.
4. IMPROVE SURFACE CONTROL OF FRACTURE PROPAGATION	4	7	4	3		low Med HIOh	4. Con..8110 conl,olllng"ac'".e geometry—risks moderate; payoll high .nd relatively .hOl1lead time.
5. IMPROVE ABILITY TO CONFIRM FRACTURE GEOMETRY AFTER STIMULATION	2	3	5	4		low Med High	5. Essonllal element in achieving p,ediclablllly .nd pos.lbly control—risks mode.ale,p.yoll high, load lime 1I10de.ala.
6. DETECT DISCRETE GAS-BEARING LENSES REMOTE FIIO"' TIIE WELLBORE	8	10	10	10		low Med HIOh	6. Very .I.ky ond long le.m, "8yolllow duo 10 long lime bolo,e lonllcula, resource Impol18nli0 opo.alo.s.
7. IMPROVE ABILITY OF LOGS TO DIFFERENTIATE RESERVOIR QUALITY	5	4	3	2		Low Med Itlgh	7. Central to .0I8cllnooa. zones and designing cost—effective stimull—risk, payoll .nd time .II •• o,abla.
•. MEASURE EFFECT OF VERY IIIGH NET CONFINING PRESSURE ON CAPILLARY PRESSURE	10	9	9			Low Mod High	8. Consonsu& I. Iha. Ihl. oblectl.o is nol vory Irnpol1onl-II affects 'ow reservol-••nd can be achlo.ed •• n••ded.
fl. IMPROVE FLUID IPROPPANT OESIGN AND PLACEMENT	6	6	6	6		Low M.d High	II. Impol1anl wo.k bll' ",ell alonOlow.,d solution—risk, p.yoll, liming favorable.
10. MEASURE FRACTURE AZIMUTH AND lENGTH DURING FRACTURE EXTENSION	6	5	6	8		Low Med High	10. Impo"onl'o, \luld de.elopmonl ond geom"lry control—high peyoll encou,aoo••osearch bill ,Iak and IlmlllO ulll.vo.abl•.

"RANKING OF INDUSTRY PRIORITY OR COMMITMENT, WITH 1 = HIGHEST, 10 = LOWEST.
2/RANKING OF TIME UNTIL COMMERCIAL APPLICABILITY, WITH 1 = SHORTEST, 10 = LONGEST.
31EXPECTED PAYOFF TO COMPANY VERSUS RISK OF R&D PROGRAM FAILING TO PROVIDE COMMERCIALLY APPLICABLE PRODUCTS. (NOTE THAT NOT ALL RESPONDENTS ANSWERED THIS QUESTION FOR ALL OBJECTIVES)
4/1NTERPRETATION OF THE AUTHORS DERIVED FROM INTERVIEW RESPONSES.

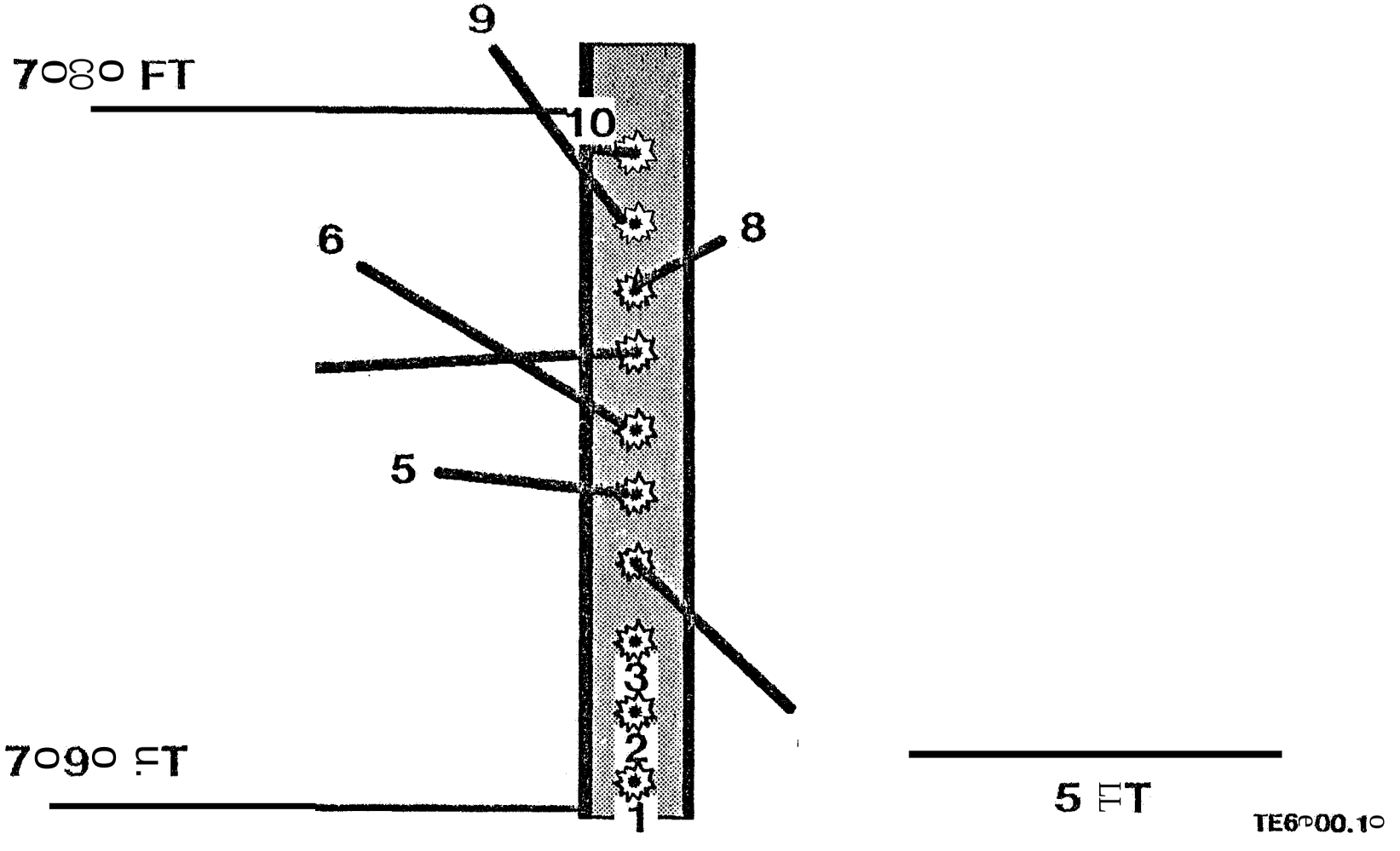
,SOURCE: BRASHEAR, J. P., L. E. ELKINS, AND M. R. HAAS, TIGHT GAS RESEARCH AND DEVELOPMENT: THE INDUSTRY PERSPECTIVE, SPEIDOE 10807, MAY, 1982.

IN SITU INSTRUMENTATION CONFIGURATIONFOR MWX!SX-1FRACTURE DIAGNOSTICS

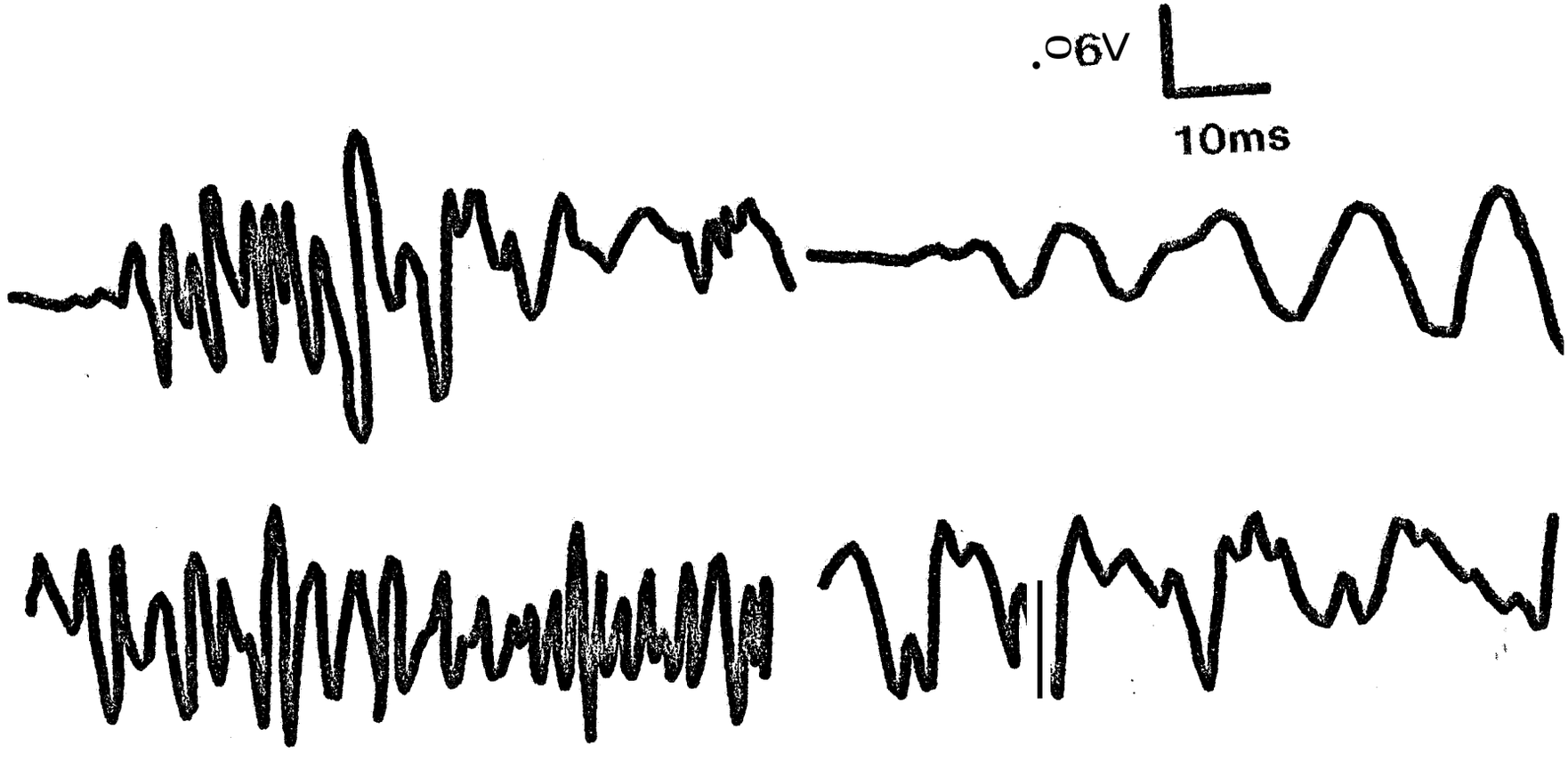


1D60000.66

ESTIMATES OF PERF SHOT LOCATIONS

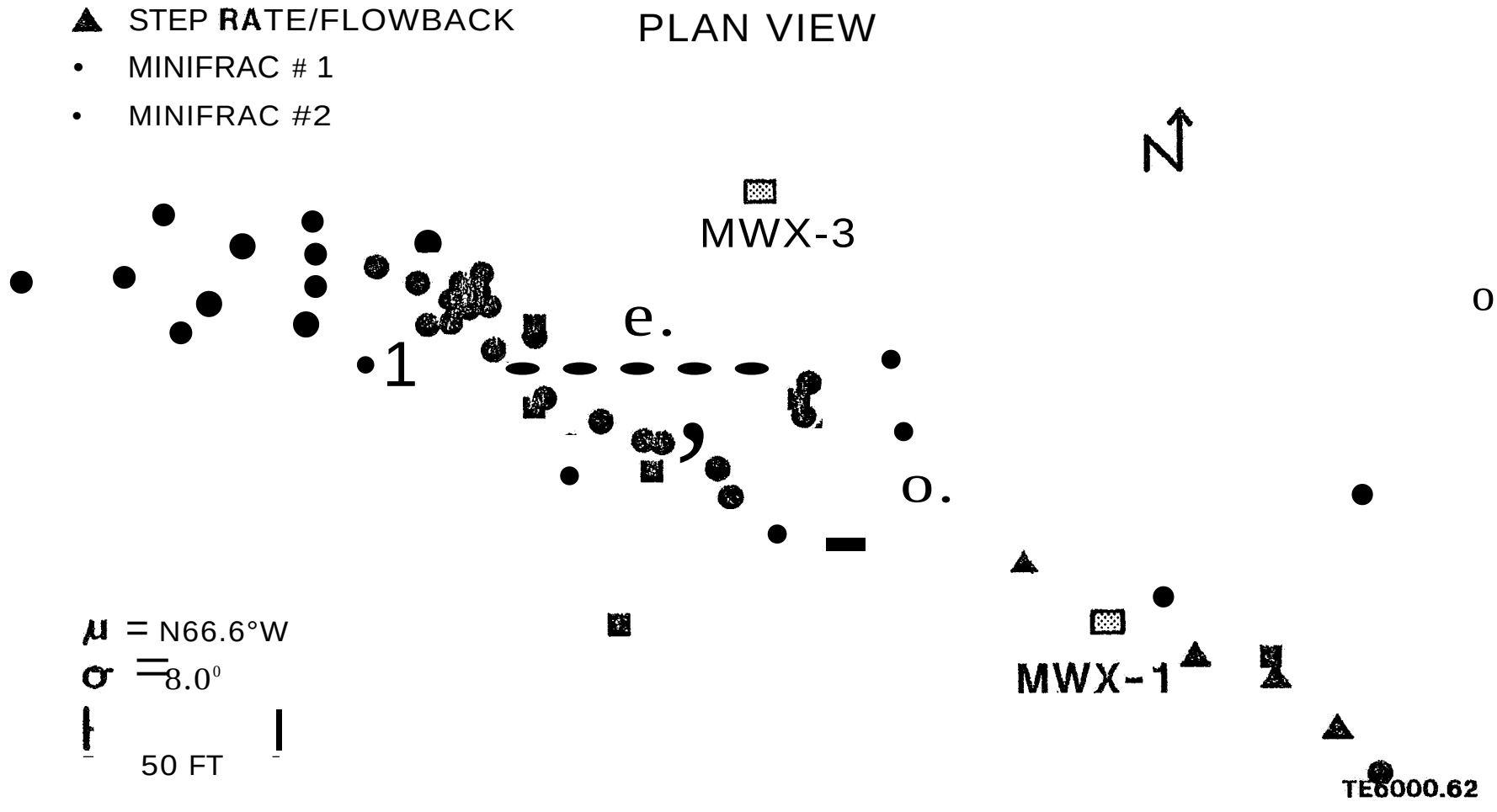


MWX/SX-1 EVENT TYPES

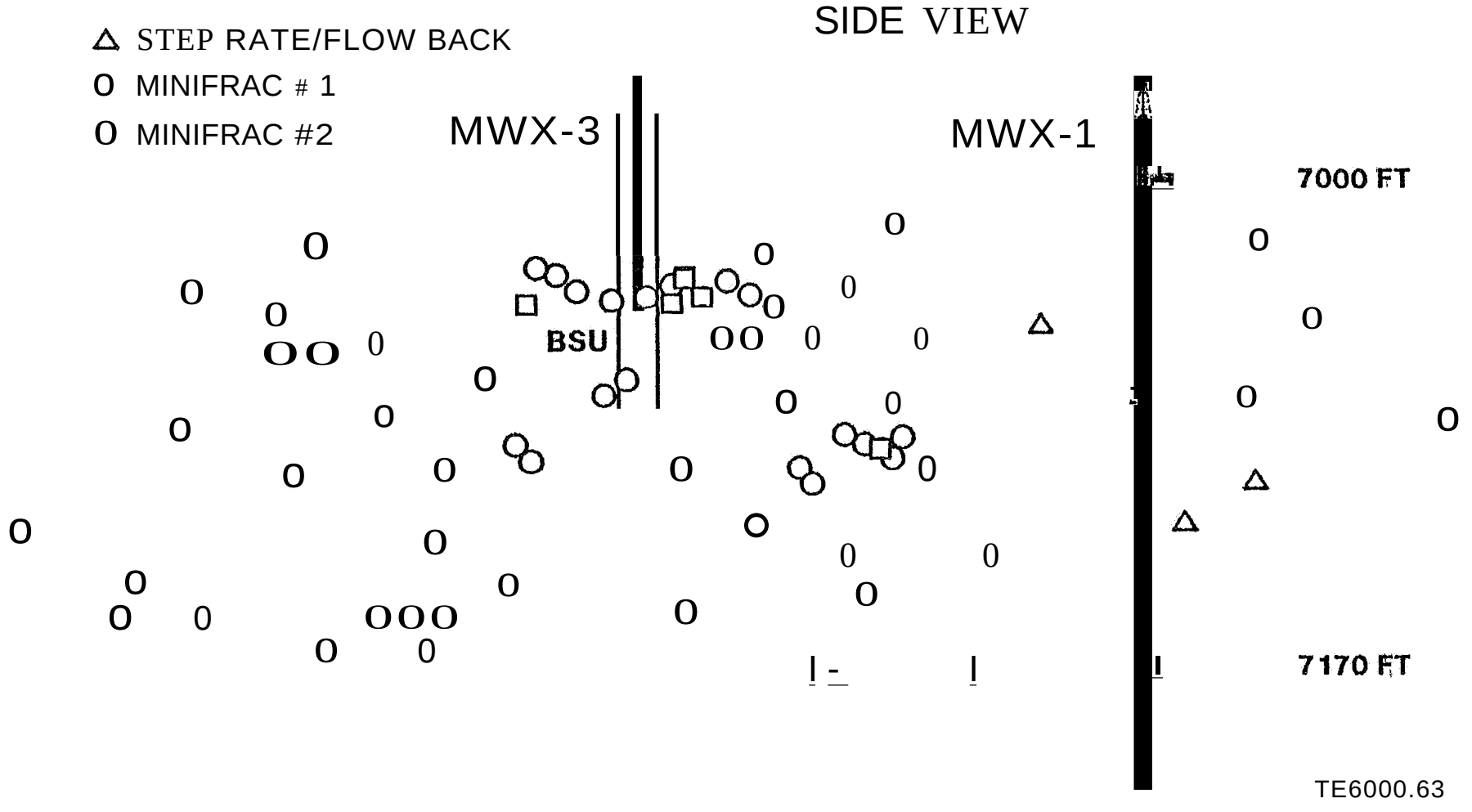


TE6000.04

MWX/SX-1BOREHOLE SEISMIC RESULTS' , ,



MWX/SX-1BOREHOLE SEISMIC RESULTS

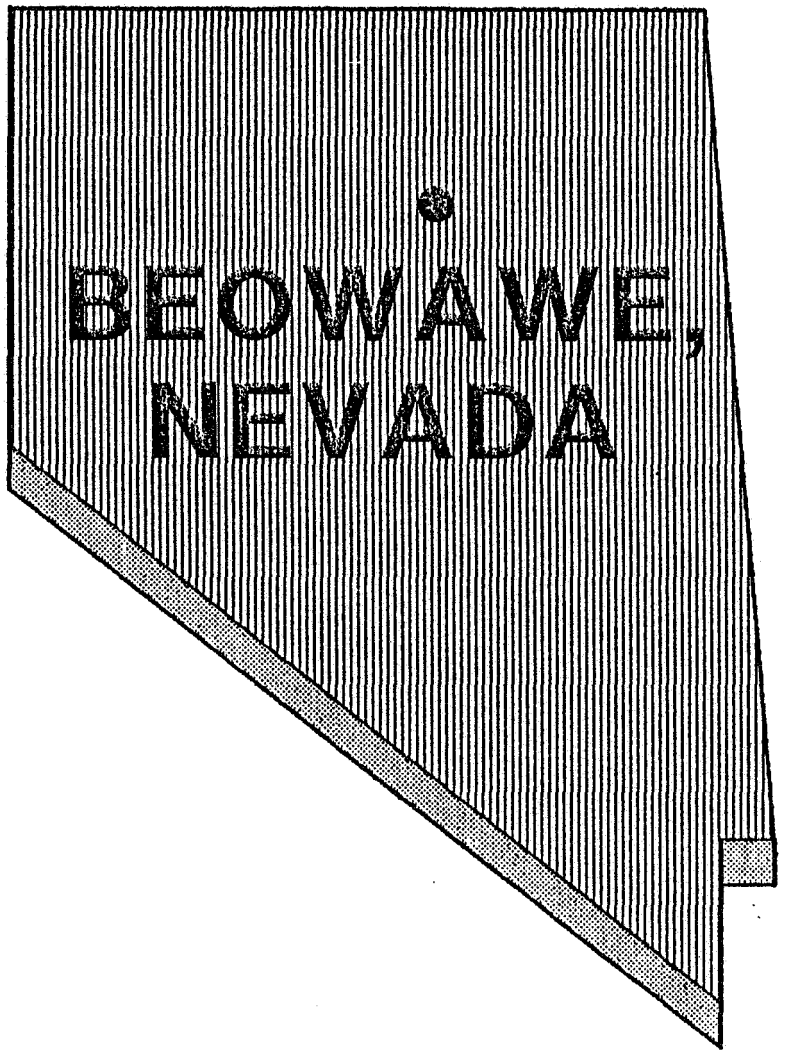


MWX/SX-1 FRACTURE DIAGNOSTICS SUMMARY

ESTIMATED FRACTURE PARAMETERS

TECHNIQUES	AZIMUTH (DEG)	HEIGHT (FT)	WING LENGTH (FT)	AVERAGE WIDTH (IN)
GEOLOGIC/CORE (PRE-FRAC)	N65 W ± 12			
TEMPERATURE LOG		150 (1110-7020)		
PRESSURE DECLINE! FLOW			440	.32
SEISMIC	N67 W ± 8	160 (7165-7005)	375 MINIMUM	

TH6000.06



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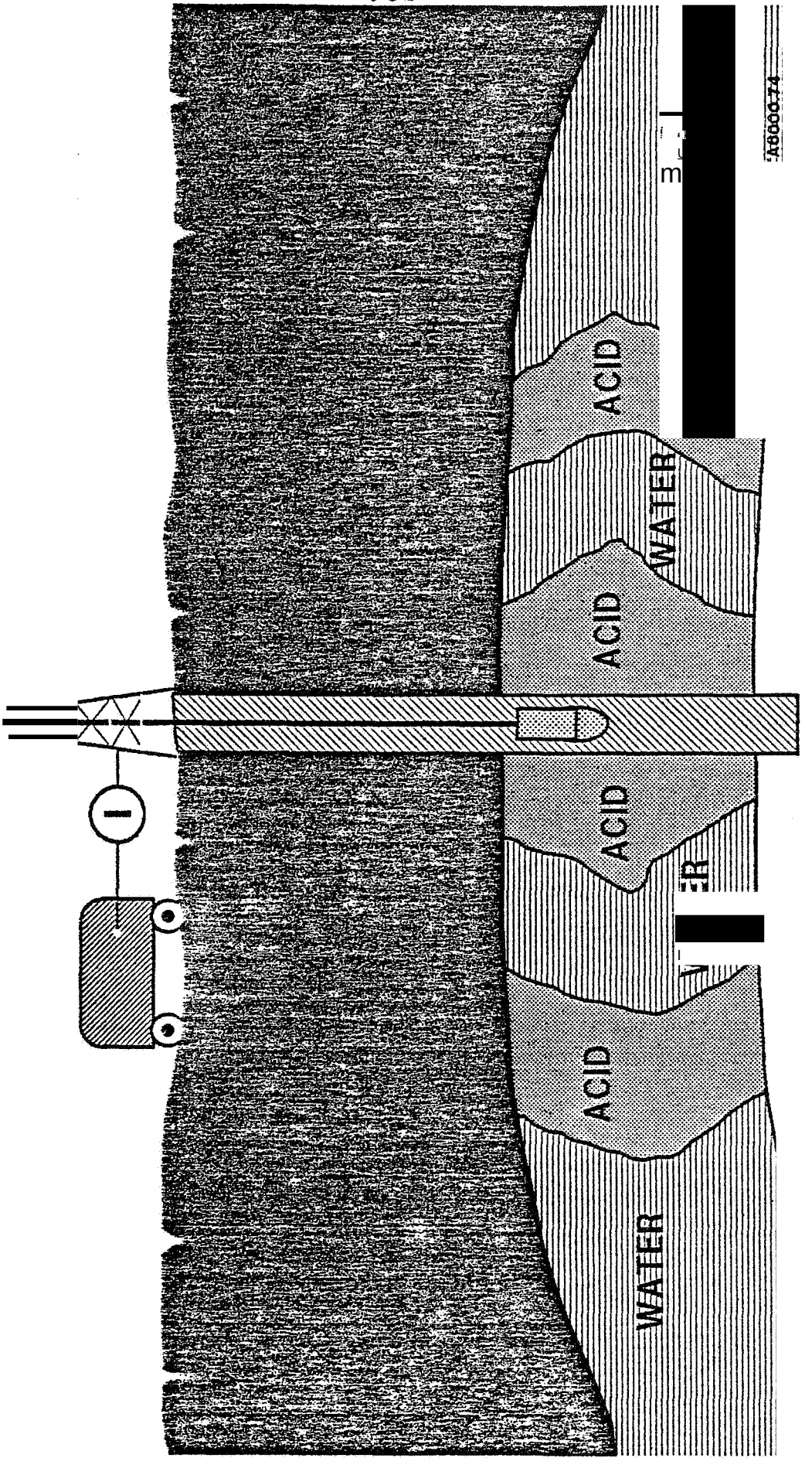
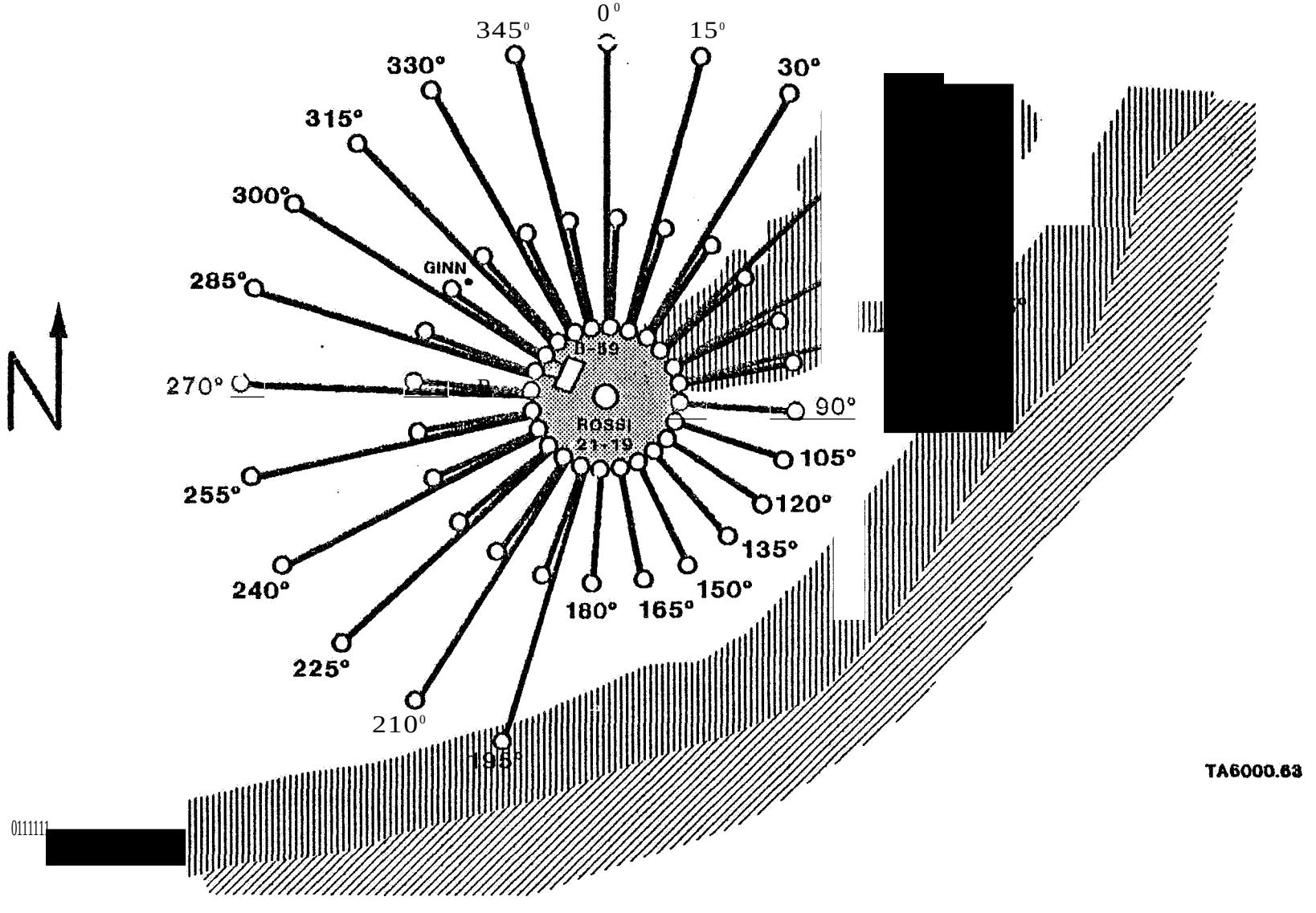


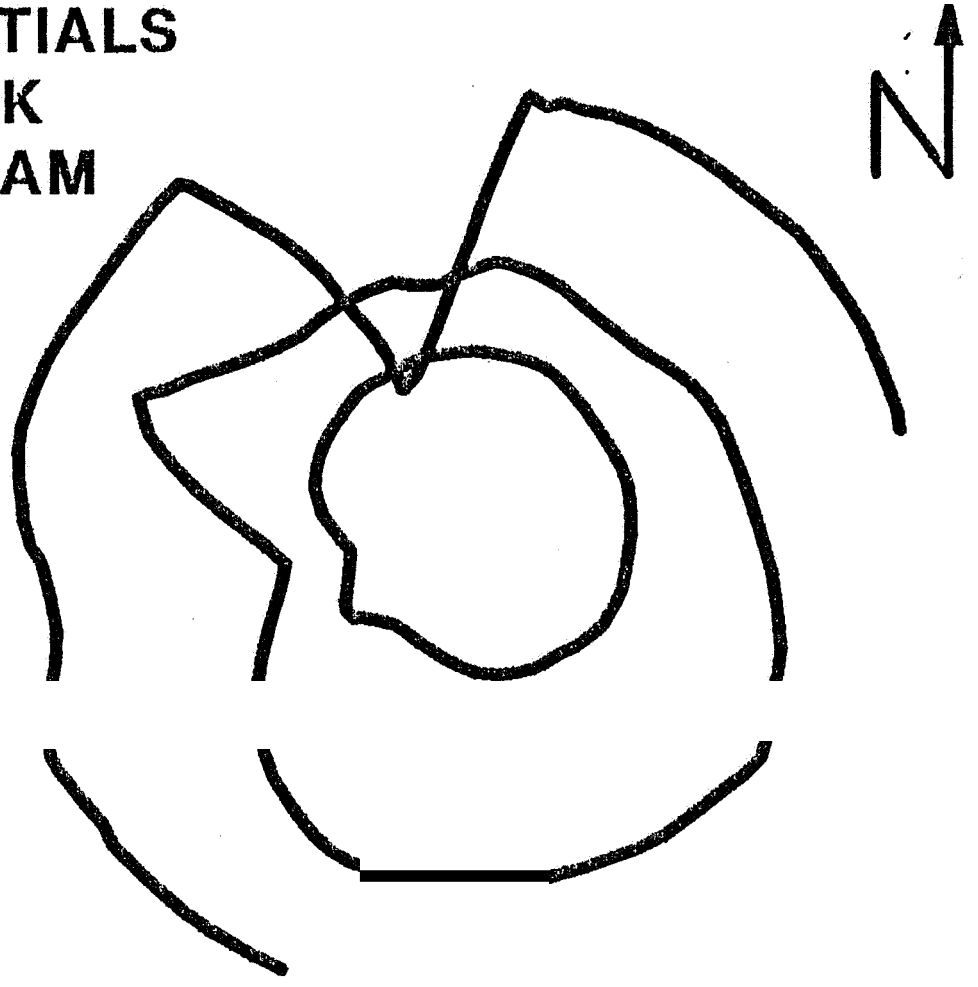
11,_-

SURFACE ELECTRICAL POTENTIAL ARRAYFOR ROSSI 21-19 ACID STIMULATION



0111111 [redacted]

PRE-FRAC POTENTIALS
WINDMILL SINK
8/17/83, 9:30 AM



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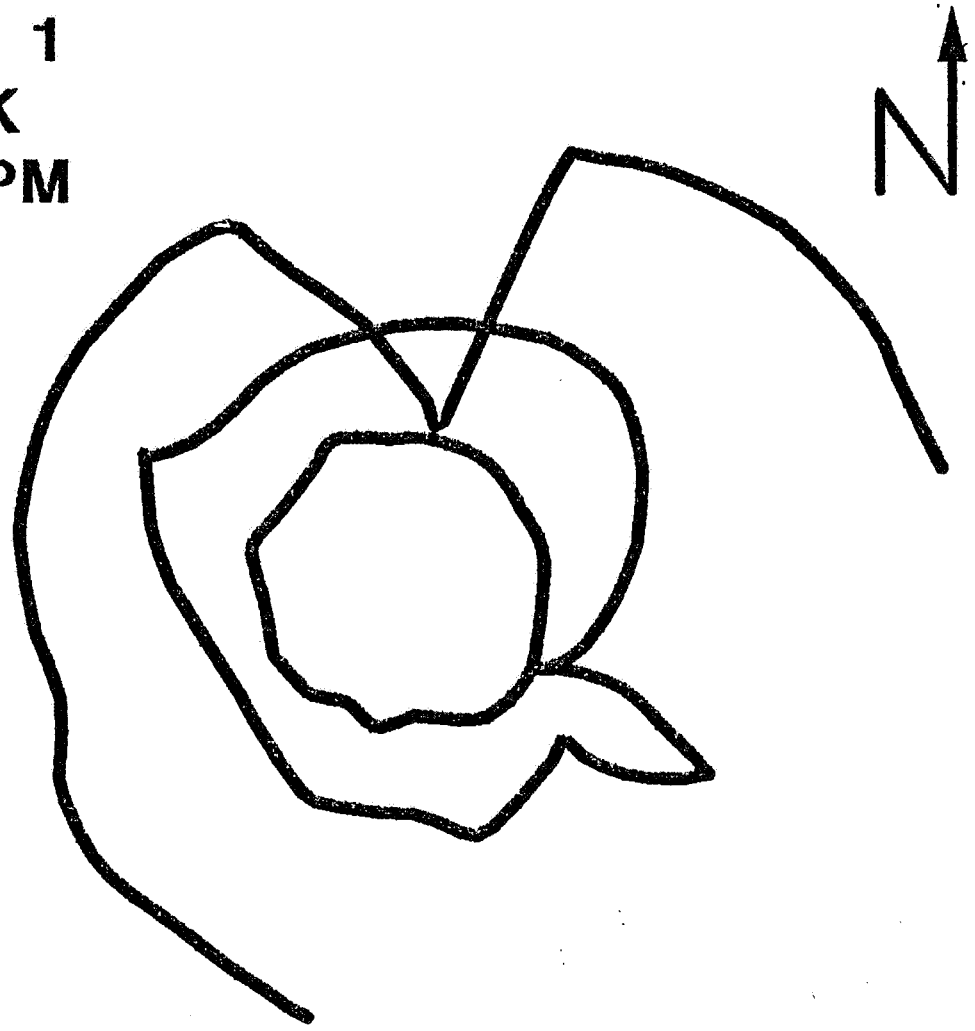
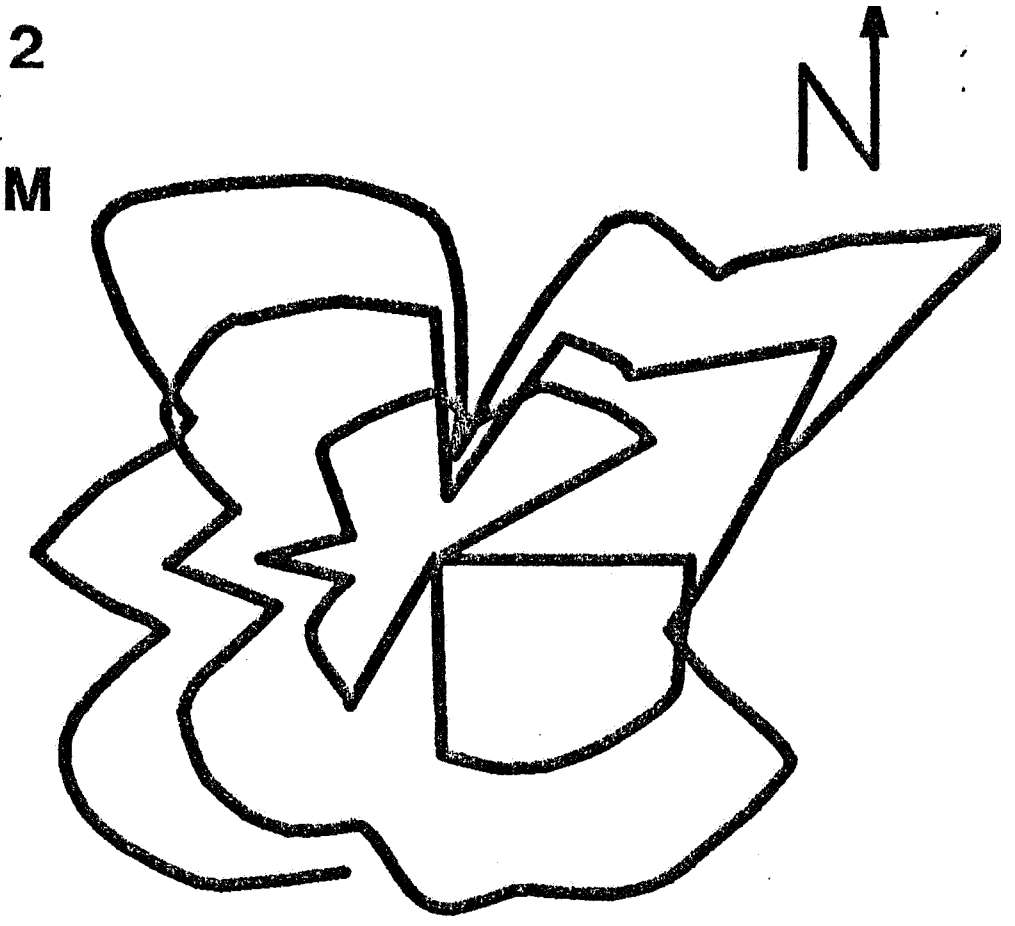
ACID INJECTION 1
WINDMILL SINK
8/21/83, 6:57 PM



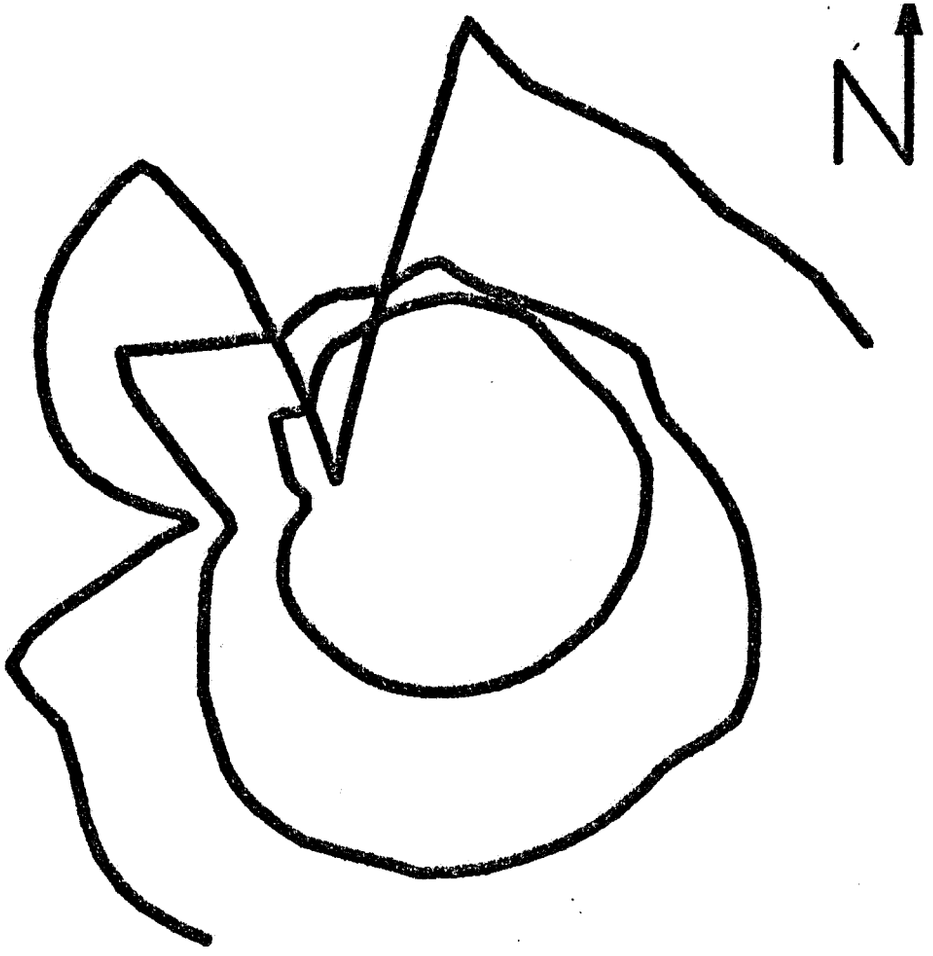
TB6000.64

ACID INJECTION 2
WINDMILL SINK
8/22/83, 6:32 PM



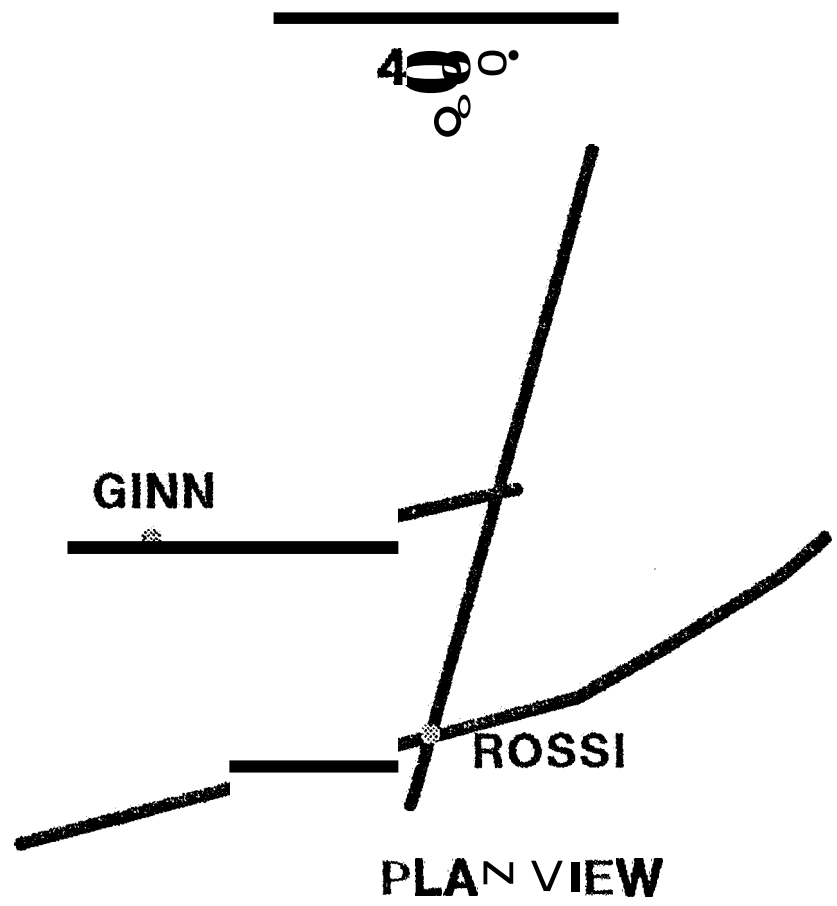
TB6000.62

POST-STIMULATION
WINDMILL SINK
8/23/83, 9:21 AM



TB6000.61

PRELIMINARY INTERPRETATION



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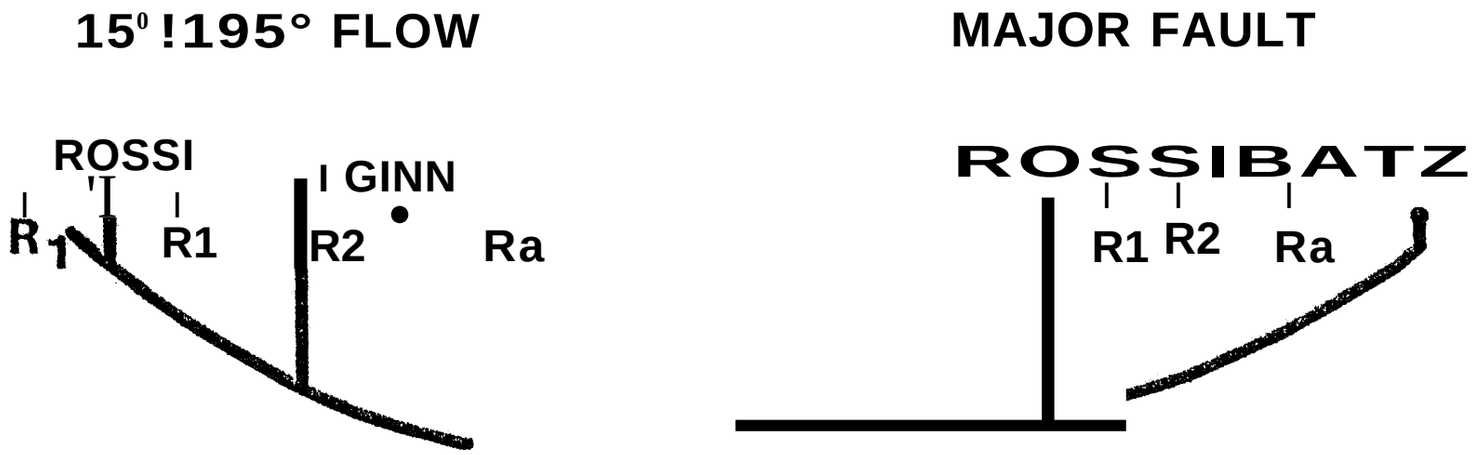
PRELIMINARVINTERPRETATION,



TA6000.81

LABORATORY MODEL TANK EXPERIMENT

ADVANTAGES:

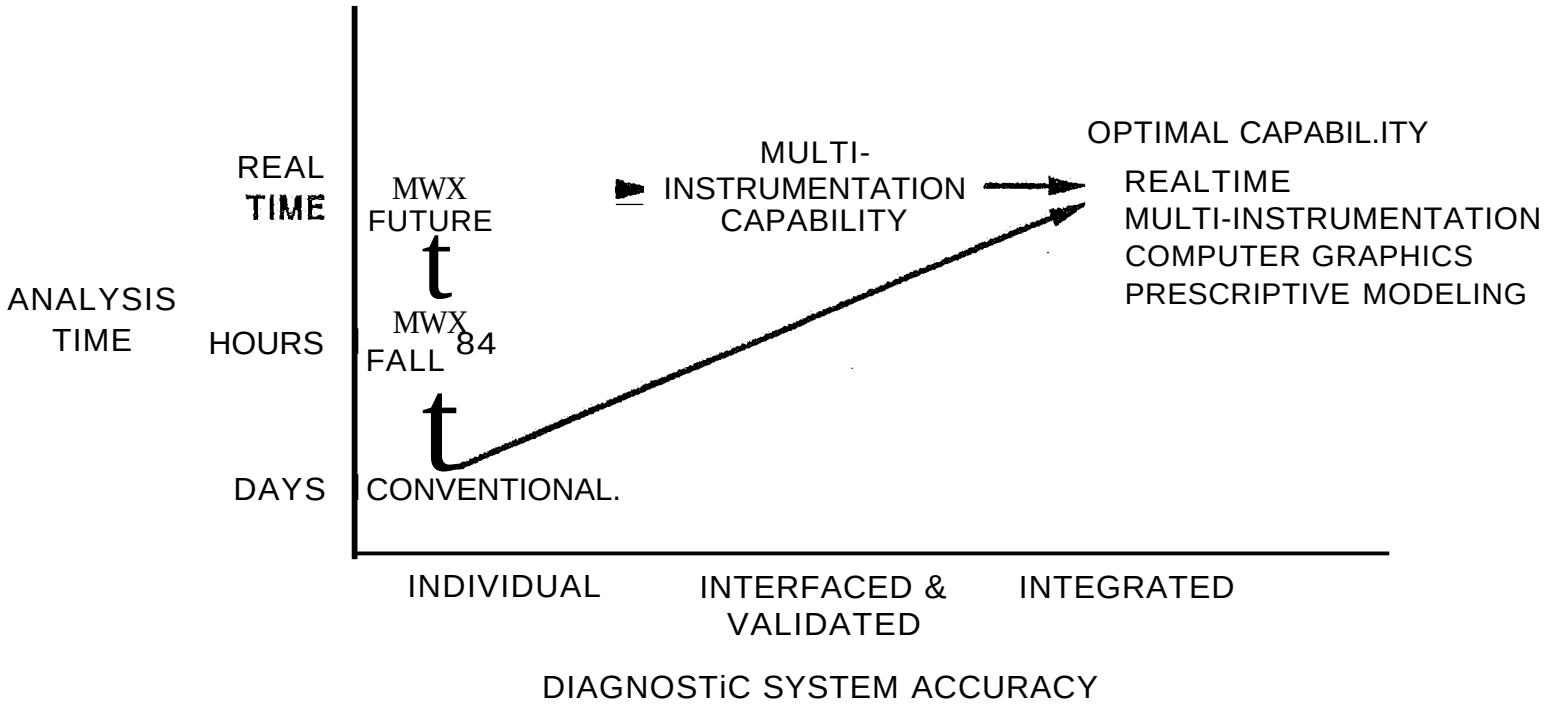
- CONTROLLABLE
- THE EXPERIIVIENTERCAN VARY:
  - RESISTIVITY OF THE MATERIALSUSED
  - MICRO-ARRAVS AND THEIR SPACING
  - NATURE, SHAPE, SIZE AND OEPTH OF POLARIZABLE BODIES
- IMPROVES QUANTITATIVE INTERPRETATION

DISADVANTAGES:

- DIFFICULT TO PRODUCE IN-SITU CONDITIONS
- DIFFiCULT TO PRODUCE CURRENT'DENSITIES AS SMALL AS THOSE IN THE FIELD

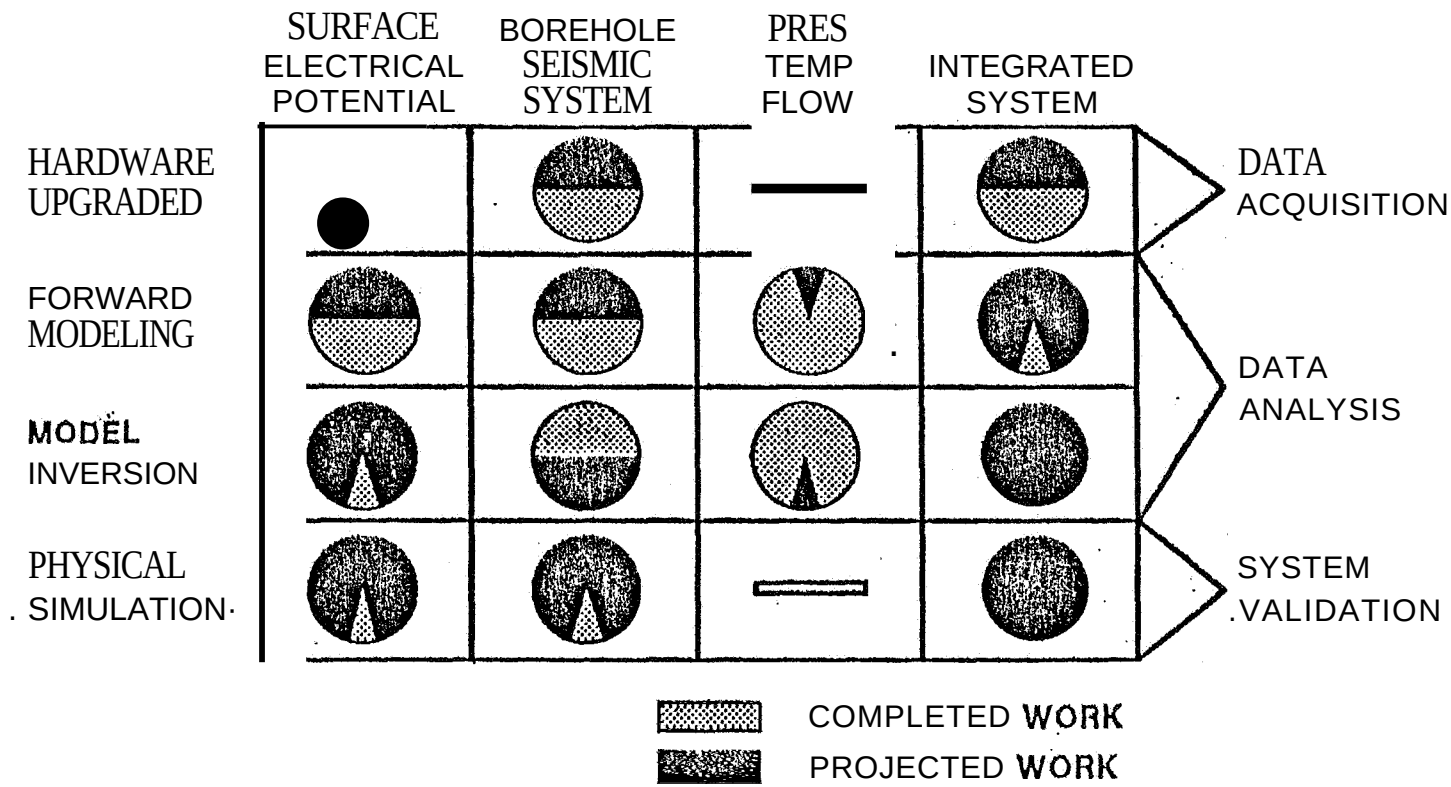
-DIFFICULT TO OBTAIN CONSISTENT RESULTS

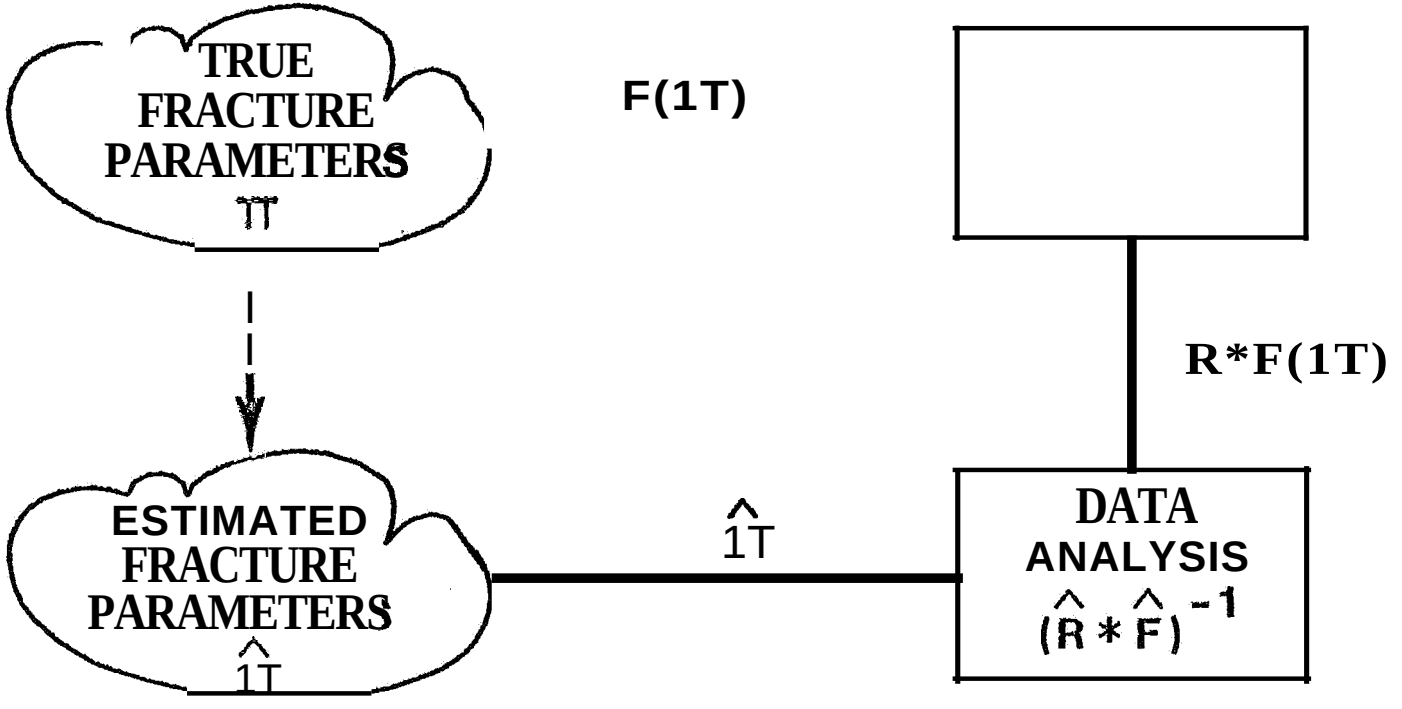
TE6000.31


ANALYSIS TIME
REAL TIME
HOURS
DAYS
MWX FUTURE
MWX FALL 84
CONVENTIONAL.
MULTI-INSTRUMENTATION CAPABILITY
OPTIMAL CAPABIL.ITY
REALTIME
MULTI-INSTRUMENTATION
COMPUTER GRAPHICS
PRESCRIPTIVE MODELING
INDIVIDUAL
INTERFACED & VALIDATED
INTEGRATED
DIAGNOSTiC SYSTEM ACCURACY

J6000.79

FRACTURE DIAGNOSTICS SYSTEM
-DEVELOPMENTAL STATUS -



TJ600077A

GENERIC INSTRUMENTATION SYSTEM