1 of 1

2OCT 20 1993
OSTI
93 OCT 28 PM 5:21**Integrated Seismic Study of Naturally Fractured Tight Gas Reservoirs****TECHNICAL PROGRESS REPORT**
for the Period: 1/1/93 - 3/31/93

Report Date 4/26/93

DOE Contract: DE-AC21-91MC28087
Principal Investigator: Dr. Gary Mavko
Co-PI: Dr. Amos NurOCT 20 1993
OSTIDepartment of Geophysics
Stanford University
Stanford, California 94305-2215**DISCLAIMER**

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MASTER

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This was the sixth quarter of the contract. During this quarter we (1) received the last of the field tapes and survey information for the seismic field data acquisition which was finished at the very end of the previous quarter, (2) began the large task of processing the seismic data, (3) collected well logs and other information to aid in the interpretation, and (4) initiated some seismic modeling studies.

The Field Site

As already reported, the field data acquisition was at Amoco's Powder River Basin site in southeast Wyoming. This is a low permeability fractured site, with both gas and oil present. The reservoir is highly compartmentalized, due to the low permeability, with the fractures providing the only practical drainage paths for production. The two formations of interest are:

- The Niobrara: a fractured shale and limey shale to chalk, which is a reservoir rock, but also its own source rock.
- The Frontier: a tight sandstone lying directly below the Niobrara, brought into contact with it by an unconformity.

The fractures are thought to lie in a roughly northwest-southeast trend, along the strike of a flexure, which forms one of the boundaries of the basin.

New Arco Participation

Early in the quarter we were able to convince Arco to join us in the technical aspects of the project. Since they also have an exploration interest in the area, they agreed to acquire two more seismic lines tying the two that were acquired by the DOE-Stanford-Amoco project. The new lines are entirely at Arco's expense, but they have indicated that they will give us full access to the data. We expect that this will greatly enhance our study, since the new lines give us a greater azimuthal coverage in the area of interest. Figure 1 shows the approximate relative locations of the new lines: lines 1 and 2 -- DOE, Stanford, Amoco; lines 3 and 4 -- ARCO.

Data Processing

The major effort during the quarter was processing the seismic data. We began by processing P-wave lines 1 and 2 to final stacks, using standard 2-D, single component processing methods and being particularly careful to preserve amplitudes. The data appear

to be of reasonably good quality. The reflectors are generally continuous on the final stacks, except near the flexure at the southwest end of line 1. We suspect that this will improve with migration.

Shear Waves

We are now processing all of the S-wave components. At this point we have taken the SH-SH, SH-SV, SV-SH, and SH-SH components of line 2 to final stack. These have been treated as single component lines -- we have not yet done any of the rotations that have become standard with this kind of multicomponent data. The stacks of SV-SV, SV-SH, SH-SV, and SH-SH show some interesting features. Figure 2 shows first-order evidence for anisotropy, and spatially variable fracture orientation. Figure 2a shows the four shear wave channels: SV-SV, SV-SH, SH-SV, SH-SH, where in each case the first pair of letters corresponds to the source polarization and the second to receiver polarization (SV refers to in-line polarization, SH refers to crossline). The timing mismatch between the SV-SV and SH-SH sections shows the usual shear-wave anisotropy. Furthermore, there is very little reflected energy in the "cross-talk" channels, SV-SH and SH-SV, suggesting that the survey line lies approximately along one of the anisotropy symmetry planes. Figure 2b shows the same arrangement of shear-wave stacks approximately 5 km to the southeast along the same survey line. In this case there are prominent "cross-talk" reflections, indicating a rotation of the symmetry axis.

We hope to clean up these lines, improve signal to noise, and get better resolutions with further processing.

Compressional Waves

It has been well established that shear wave splitting indicates anisotropy, but in most surface seismic surveys only P-wave signals are recorded. While the shear wave data are usually not available, P-wave data of crossed lines are a possible source of information of the variation of rock properties with orientation. Although P-waves are often not as sensitive an indicator of fracture-related anisotropy as shear wave splitting, usually they have a much higher signal to noise ratio, and their amplitudes are more reliable. We have begun some prestack P-wave AVO analysis to search for correlations between the P-wave AVO pattern and the occurrence of fractures.

Our initial approach was to simply measure average amplitude of every trace in a 1.0-second window around the zone of interest, containing the Frontier and Niobrara events. The amplitudes for the entire line were then decomposed in a surface-consistent manner so that source, receiver, offset, and cdp effects could be determined. The source and receiver

effects were the largest, by far. The preliminary results for line 2, with the source and receiver effects removed, are displayed in stacking-chart form in Figure 3. In this type of display, vertical patterns or streaks are receiver-consistent, horizontal streaks are shot-consistent, streaks parallel to the main diagonal are offset-consistent, and streaks normal to the main diagonal are cdp-consistent. (In this case, there still remains a checker-board pattern that is probably related to daily changes of SGR recorders, amplifiers, etc. We will attempt to correct for these systematic changes also.) We find that this is a very informative and robust type of display, since virtually any trace attribute can be displayed with a minimum of processing. Figure 3 shows a very preliminary indication of offset-dependent amplitude patterns which vary along the line. This coincides with the variation along the line of the anisotropic rotation that we observed with the shear waves.

Of course this is very preliminary. To improve the reliability of any amplitude information we need to further correct for the acquisition-consistent "checker-board" and separate, as much as possible, the reflections from the random and coherent noise prestack.

Well logs

We have acquired, through the Wyoming Oil and Gas Commission, well log suites from six wells in the area (see Figure 1 for locations), and are attempting to obtain, through ARCO, logs from several more wells to build cross-sections through the area of interest. We have some digitized logs from three of the six wells, and hope to either begin digitizing the remainder soon, or acquire the digital well data from ARCO. In addition, we are beginning to look at regional structural and stratigraphic variations within the Frontier and Niobrara in order to better integrate the seismic and well log data with the depositional systems and expected fracture trends.

The log suite for one of the wells, the Apache #36-1 State, contains a fracture identification log on which we have performed some preliminary analysis. This location is of special interest since it directly ties the southeastern part of line 2 in an area of a possible anisotropy and change in the fracture orientation, as discussed above. Examination of this log, which is based on the dipmeter, indicates that the Niobrara and Frontier both contain fractures, which show two probable dominant orientations: one approximately N60°E to N70°E, and the other N40°W to N60°W. The northwest-southeast orientation agrees with that found by a Colorado School of Mines investigation of the Niobrara Formation at Silo Field near Cheyenne, southeast of the study area (Lewis *et al.*, Dec. 1991 Geophysics). Discussions with Amoco personnel indicate that they believe that the regional flexure trend

changes from a WNW orientation to a NNE orientation towards the eastern end of line 2. The possible "conjugate" fracture set may reflect this change, however, more detailed analysis is needed to support this contention.

Plans for next quarter.

Our major effort this quarter will again be to process the seismic data. We will also be continuing with the theoretical seismic modeling in order to understand some of the reflectivity and amplitude anomalies that we have found. We will be digitizing the logs in order to build a better subsurface model; estimating corresponding shear velocities using the known stratigraphic column, and then proceeding with the raytrace modeling.

DOE Fractured Reservoir Project - Base Map

Figure 1. Map showing relative orientations of the survey lines and some of the wells where we have obtained log information.

Figure 2a. Four components of shear-wave stack from the DOE-Stanford-Amoco fractured reservoir study. Travel-time differences between SH-SH and SV-SV stacks show anisotropy.

Figure 2b. Similar to 2a, for a location about 5 km to the southeast along the same line. The appearance of strong reflections on the cross-talk channels, SH-SV and SV-SH, suggests a large rotation in the fracture directions.

Figure 3. Stacking chart display of preliminary amplitudes along line 2.

Record 1 of 1 -----

Req. No: RQ3752 Date Written: 03/11/93
Status: Placed (DISPLAY ORDER for P.O. data) by Muir, Margaret
Capital Equip.: No
Dept: GEOPHYSICS (SRB) Attachments: No

RQ37520: Placed, Not Paid
Charge: 2BCZ759-94611 100% (ENERGY DE-AC21-91MC28087)
Taxability to be determined by final dollar amount.

Deliver: MARGARET MUIR, 317A MITCHELL, 2215, Date Ordered: 03/09/93
STANFORD, CA 94305-2215

Vendor: MCKEE WELL HISTORY
Address: PO BOX 842
CASPER, WY 82602
Phone: 307/237-3388
Talk to: CHRISTINE ROGERS

Line Items			
Qty	Unit	Unit Price	Ext. Price
1	EA	\$ 380.00	\$ 380.00
1 invoice 3354 for well history as per fax request - see attached			
LINE ITEMS TOTAL:			\$ 380.00
TAX:			\$ 31.35
TOTAL INCLUDING TAX:			\$ 411.35
=====			

Requested by: MARGARET MUIR, 723-0839, MARGARET@PANGAEA
Contact Name: MARGARET MUIR, 723-0839
Return Paperwork to: MARGARET MUIR, 317A MITCHELL, 2215

Routing Information			
Order	Route	Remark	Action
Orig	margaret muir (3-0839)		Approved 03/11/93 Sign
11	Accounts Payable		FYI Sent 03/11/93 FYI

No remarks added during routing.

MAR 03 '93 11:23 STANFORD/GEOPHYSICS

To: Chris Rogers,
McKee Well History
Casper, Wyoming

From: Robert D. Walters
Postdoctoral Research Associate
Rockphysics and Borehole Project
Department of Geophysics,
Stanford University
Stanford, CA 94305-2215

Chris,

Here is our finalized list of four wells for which we would like copies of all available logs. I assume that the deviated well (the Impel #1 Wallis) comes with directional survey coordinates. Please ship the logs to me at the above address. You can bill us when you send the work. If you have any questions, please feel free to call me at the number listed below. Thanks.

Operator	Well Name	Location	TD	API Number
✓ Apache Corp.	#36-1 State	T33N R71W s36	13015	21874
Impel	#1 Wallis	T33N R71W s23	12772	20915
Czar Resources	#1 Bennett 28-1	T33N R71W s28	12832	21953
✓ Exxon Corp.	#1 Box Creek	T33N R71W s19	13303	22464

Rob Walters

(415) 723-0166
(415) 725-7344 (fax)

Transfer of Expense # 719AU 03/31/93 1 Items 20 Lines Tot.Cr 4,446.00. (To change Geophysics/SRB account numbers.) [Last approved by Wright on 03/22/93.]

Originated 03/22/93 by Kai Lanz (3-3400) Status: ACTIVE

TRANSFER OF EXPENSE
TITLE: ELECTRONIC SHOP SERV
STATUS: ACTIVE

TO ALLOCATE ELECTRONIC SHOP SERVICES TO THE DEPARTMENTS IN THE SCHOOL OF EARTH SCIENCES, FOR THE USAGE IN FEBRUARY'93. RATE FOR 92-93: \$38/HOUR

LINE FUND	ACCOUNT	GL DEPT. REF	DESCRIPTION	CHARGE	CREDIT
005	107R003	9-BAZ072	94001 KAI ALLOCATION Feb-93		4,446.00
			ORIG.MO/YR		
010	111C111	1-BAZ009	94647 KAI Computer Comm- 39hrs	1,482.00	
			ORIG.MO/YR		
015	111C111	8-BAZ003	94647 KAI Development- 1hr	38.00	
			ORIG.MO/YR		
030	111C111	1-BAZ001	94647 KAI Staff, Forsythe- 5hrs	190.00	
			ORIG.MO/YR		
045	152M805	1-BDZ215	94647 KAI Einaudi, ODEX- 4hrs	152.00	
			ORIG.MO/YR		
050	172R299	1-BDZ628	94647 KAI D. Pollard Mac - 1hr	38.00	
			ORIG.MO/YR		
055	111C111	1-BDZ001	94647 KAI AES dept, class- 6 hrs	228.00	
			ORIG.MO/YR		
060	172G448	1-BDZ627	94647 KAI Irwin's HP- 2hrs	76.00	
			ORIG.MO/YR		
065	163D325	2-BBZ423	94647 KAI Stebbins, Eliz- 1hr	38.00	
			ORIG.MO/YR 02/93		
070	172S233	1-BDZ613	94647 KAI R. Lyon SRS Lab- 23hrs	874.00	
			ORIG.MO/YR		
075	172P177	1-BEZ604	94647 KAI Angharad's Mac- 3hrs	114.00	
			ORIG.MO/YR		
080	122G015	1-BCZ103	94647 KAI M. McWilliams lab- 5hrs	190.00	
			ORIG.MO/YR		
085	172S327	1-BCZ623	94647 KAI S. Klempner - 3hrs	114.00	
			ORIG.MO/YR		
090	111C111	1-BCZ001	94647 KAI D. Moos- 3hrs	114.00	
			ORIG.MO/YR		
095	183X005	2-BCZ759	94647 KAI A. Nur/M. Muir - 8hrs	304.00	
			ORIG.MO/YR 02/93		
100	183X005	2-BCZ759	94647 KAI G. Mavko- 2hrs	76.00	
			ORIG.MO/YR 02/93		
105	111C111	1-BBZ001	94647 KAI J. Wright- 4hrs	152.00	
			ORIG.MO/YR		
110	163D191	2-BBZ416	94647 KAI J. Bargar- 1hr	38.00	
			ORIG.MO/YR 02/93		
115	111C111	1-BDZ002	94647 KAI Dept. computers/5 hrs	190.00	
			ORIG.MO/YR 02/93		
120	172P192	1-BDZ609	94647 KAI Harbaugh/1 hr.	38.00	
			ORIG.MO/YR		

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ELECTRONICS SHOP WORK ORDER NO. 93 GM 21

Person requesting work: G. MAVKO Date Feb. 93

Account no. to be charged: 1. Bcz. 620

Priority: () extremely urgent () needed soon () no hurry

Estimated time required for job: _____ hours. Est. completion date _____

Brief Description of Job:

Net & Terminal wiring

Record of work:

[illegible]

Total no. hours required for job: _____ Date completed: _____

ELECTRONICS SHOP WORK ORDER NO. 93 AN 21

Person requesting work: M. MUIR / A. NUR Date Feb. 93

Account no. to be charged: 1. BCZ.620

Priority: ☐ extremely urgent ☐ needed soon ☐ no hurry

Estimated time required for job: _____ hours. Est. completion date _____

Brief Description of Job:

Record of work:

[illegible]

Total no. hours required for job: _____ Date completed: _____

SUFIN Journals

March 17, 1993

JOURNAL NO: 717CH
MONTH END: 03/31/93TRANSFER OF EXPENSE
TITLE: TRANSFERS FROM SRB

STATUS: ACTIVE

ACCOUNT GL DEPT. REF DESCRIPTION

CHARGE CREDIT

prorating charges to grants and contracts as budgets allow. kinkos prorating
is less the original amount as our current grants and contracts do not
have any more monies allocated in this slot. these charges are for 2/93.

005	172R113	1-BCZ620	94611	RP5432	macconnection/supplies	ORIG.MO/YR 02/93	184.30	319.09
010	169J196	2-BCZ424	94611	RP5432	macconnection/supplies	ORIG.MO/YR 02/93	134.79	
015	167G033	2-BCZ499	94611	RP5432	macconnection/supplies	ORIG.MO/YR 02/93	179.27	
020	172R113	1-BCZ620	94613	02003	mailing services	ORIG.MO/YR 02/93	126.50	
025	172R113	1-BCZ620	94613	89300	mailing services	ORIG.MO/YR 02/93	179.27	
030	169J196	2-BCZ424	94613	02003	mailing services	ORIG.MO/YR 02/93	20.73	
035	169J196	2-BCZ424	94613	89300	mailing services	ORIG.MO/YR 02/93	105.77	
040	167H023	2-BCZ423	94613	89300	mailing services	ORIG.MO/YR 02/93	1,786.11	
045	172R113	1-BCZ620	94615	C79243	kinko's	ORIG.MO/YR 02/93	850.00	
050	169J196	2-BCZ424	94615	C79243	kinko's	ORIG.MO/YR 02/93	600.00	
055	167H023	2-BCZ423	94615	C79243	kinko's	ORIG.MO/YR 02/93	336.11	
060	167G033	2-BCZ499	94615	C79243	kinko's	ORIG.MO/YR 02/93		
phone charges prorated on contract that has monies allocated for phone charges.								
005	172R113	1-BCZ620	94650	02006	phone charges	ORIG.MO/YR 02/93	600.00	
010	183X005	2-BCZ759	94650	02006	phone charges	ORIG.MO/YR 02/93	600.00	
JOURNAL TOTAL								3,010.97

STATUS: ACTIVE

ORIGINATOR: muir, margaret

Order	Route	Remark	Action	Date	Sign
Orig	margaret muir (3-0839)		Approved	03/17/93	Sign
12	Expend/Aux Acctg 1 (Sashi 3-2989)	(none)			Sign

No remarks added during routing.

Communication Services

STATEMENT

BILLING DATE ENDING

FEBRUARY 21, 1993

Communication Services has lowered its 'Night' rates for long-distance calls in Zone D of the Stanford service area. This includes cities such as north San Francisco, south San Jose, Santa Cruz and Walnut Creek.

Account: 1-BCZ620
Department: GEOPHYSICS
Location: MITCHELL 366
STAR: FARWELL, LINDA

SUMMARY OF CHARGES

Period	Monthly Services	Billable Calls	Other Services	Total
This Month	\$452.50	\$577.14	\$42.50	\$1072.14
This Year to Date	\$2762.24	\$3144.86	\$206.00	\$6113.10

DETAIL OF MONTHLY SERVICE CHARGES

PDN	Name	Service	Description	Reference	Amount
3-0166	ROCK PHYSICS LAB	V002	Basic Line-Pkg A	04 560-909A	23.50
		MLBW	Maint-Link Basic	04 560-909A	0.50
		Y101	Local Calling Area	04 560-909A	14.25
3-0839	MUIR, MARGARET	V032	Multiple Line-Pkg D	04 560-345B	39.50
		METD	Maint-ET Set	04 560-345B	3.25
		Y101	Local Calling Area	04 560-345B	14.25
		F041	Voice Mail for box #30839		6.50
		F014	Message Waiting	04 560-345B	No Charge
3-1188	FAX LINE	D002	Basic Modem Line	04 560-344D	23.50
		Y101	Local Calling Area	04 560-344D	14.25
3-9438	MAVKO, GARY	V012	Standard Line-Pkg B	04 560-316A	28.50
		MLBD	Maint-Link Basic	04 560-316A	0.50
		Y101	Local Calling Area	04 560-316A	14.25
		F041	Voice Mail for box #39438		6.50
3-9526(M)	AMOS NUR	V022	Enhanced Line-Pkg C	04 560-344A	33.50
		V022	Enhanced Line-Pkg C	04 560-311A	33.50
		ME1D	Maint-ET Set/Add-on	04 560-344A	4.25
		Y101	Local Calling Area	04 560-344A	14.25
		Y101	Local Calling Area	04 560-311A	14.25
5-1345	STUDENT OFFICE	V002	Basic Line-Pkg A	01 080-206A	23.50
		MLBD	Maint-Link Basic	01 080-206A	0.50
		Y101	Local Calling Area	01 080-206A	14.25
5-7037	HAGAI RON	V002	Basic Line-Pkg A	04 560-922A	23.50
		Y101	Local Calling Area	04 560-922A	14.25
5-7753	FAX LINE	D002	Basic Modem Line	04 560-345A	23.50
		Y101	Local Calling Area	04 560-345A	14.25
5-9296	DVORKIN, JACK	V012	Standard Line-Pkg B	04 560-347D	28.50
		ML4D	Maint-Link+4	04 560-347D	0.50
		Y101	Local Calling Area	04 560-347D	14.25
		PM00	Voice Mail	-	6.50
		F015	Message Waiting	04 560-347D	No Charge

SUB TOTAL - MONTHLY SERVICE CHARGES

\$452.50

**DATE
FILMED**

12 / 13 / 93

END