ACID ETCHING AND REACTION RATE EVALUATION IMPROVE STIMULATION RESULTS

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ABSTRACT
Stimulation of carbonates with acid has been and will continue to be one of the most economical means of improving the performance of both production wells and injection wells. Performance improvement is accomplished through the proper match-up of fluids and techniques to the reservoir

The beginning of a successful stimulation starts with an understanding of the reservoir composition and pore system. Having defined these reservoir properties, an evaluation of fluids which will not only achieve the best differential etching in the carbonate but will also maintain rock integrity to withstand closure of conductivity pathways created by acidization comes next. Lastly, control of leak-off and reactivity for placement to insure deepest penetration and conductivity is considered.

Presented are examples of implementation of the above evaluations, which have resulted in successful stimulations. These case histories cover a wide range of reservoir conditions and geographical areas.

BACKGROUND

Acidization has long been utilized as a stimulation technique for carbonate reservoirs. Early acid jobs were inelegant and consisted, frequently, of small volume acid dumps down the wellbore with the hope of production improvement in the near wellbore region through the dissolution of near wellbore rock. Little attention was given to the rock type (limestone, dolostone, a mixed carbonate, shaley, sandy, or anhydritic) and pore system morphology, to the "hardness" or "softness" of the carbonate, and virtually no attention was given to the manner in which acid reacted with the rock, either relative to etch patterns or to rates of reaction.

Subsequently, and with improvements in pumping equipment and the development of inhibitors, the acidization of carbonates could occur with higher volumes of acid and higher pump rates. Quasi reaction rates were determined by static rate testing, and success was assumed, relative to the generation of a conductive fracture. Treatments did, occasionally, fail, and workers began examining the actual rock, relative to the rock composition, the rock hardness, etching patterns developed on rock surfaces, **and** dynamic rates of dissolution of the carbonate in acids of various strengths.

For the past several years, considerable attention has been given to the improvement of carbonate acidizing and acid fracturing by determining applicable rock properties (composition, strength, hardness, the pore system morphology), by determining acid reaction rates specifically for the reservoir of interest, and by determining etching patterns.[1-4]

In this paper, detailed laboratory studies and corresponding field results are discussed. As possible, comparisons are made with previous acid treatments.

EXPERIMENTAL

Rock Mechanical Properties

Cylindrical core plugs, 1 inch diameter and approximately 1.0 to 2.0 inches in length, are drilled from whole core sections, using Isopar L oil or KCl water. Plug ends are then ground flat and parallel to within a tolerance of 0.001 inch. Samples are left in the as-received condition.

A non-destructive method of measuring the dynamic elastic properties of each sample is performed first. This is accomplished by measuring the ultrasonic compressional and shear wave velocities using a standard pulsed through-transmission method. To achieve this, shear and compressional mode transmitting and receiving transducers are simultaneously placed on opposite surfaces of the sample. The transmitting transducers are energized using a high voltage spike pulser (900 volt max.). Both the shear wave and converted compressional wave ("p-wave") signals are amplified, band-pass filtered, and displayed on an oscilloscope where the signals' first peak arrival times are measured. The signal peak frequency is 1 MHz. The wave speeds of the compressional and shear modes are calculated by dividing the time of arrival of a particular propagation mode into the length of the sample. Corrections, due to small inherent signal delay times, are applied to the signal arrival times prior to velocity calculations. The bulk density of each sample is calculated from the ratio of weight to volume, with the bulk volume being calculated from independent caliper measurements of sample length and diameter.

The dynamic Poisson's Ratio and Young's Modulus are calculated from the ultrasonic wave velocities (both p-wave and s-wave) and bulk density using Equations (1) and *(2)*. These equations were derived under the assumptions that the sample possesses linear elastic, homogeneous, and isotropic behavior. The dynamic Poisson's Ratio (PR) is calculated from the expression:

$$PR = (0.5(Vp/Vs)^2 - 1)/((Vp/Vs)^2 - 1) \qquad (1)$$

Vp and Vs are the compressional and shear wave velocities, respectively. The dynamic Young's Modulus (E) is calculated from the expression:

$$E = 2^* \rho_b (V_s)^2 (1 + PR) \qquad (2)$$

ρ_b is the bulk density of the sample.

Alter completing ultrasonic measurements, samples are subjected to uniaxial stress measurements, in which the unconfined compressive strength and static Young's Modulus and Poisson's Ratio are determined. Samples are placed in the hydraulic press of a MTS 0.5 million pound load frame. Two linear variable differential transformers (LVDT's) are mounted to a bracket that allows them to hang parallel to the axis of the sample under test. These LVDT's measure the axial displacement of the sample during axial loading. A circumferential LVDT apparatus independently measures the radial displacement. Samples are axially loaded under computer control at a constant strain rate of 0.05% strain per minute. Tests terminate at sample failure. The static Young's Modulus is calculated from the linear portion of the axial stress-strain curve. The static Poisson's Ratio is calculated from the slope of the radial-axial strain curve. The unconfined compressive strength is taken as the maximum load at failure.

Acid Etching

Hydrochloric acid reacts with acid-soluble minerals at different rates. In a rock containing a mixture of minerals, the more rapidly reacting ones will dissolve faster leaving raised areas where the less reactive minerals occur. Likewise, differences in particle size can create differential etch patterns that result in a highly conductive fracture when a carbonate formation is fractured with acid. The ability of an acid-etched fracture to remain open without the use of proppant can be evaluated by acid etching tests. The etched surface is subjectively evaluated as to its roughness and relief (height difference between high and low points).

A whole core sample is sawed with a diamond-bladed saw to create a flat vertical surface. The core is suspended in a large beaker containing hydrochloric acid at a specified concentration and temperature, for a specific time interval. The core is removed from the acid and rinsed with water to quench the reaction. The surface of the acidized formation sample is examined and photographed. Sample surfaces are compared before and after etching.

Brinell Hardness

In formation fracturing applications, it may be necessary to determine the Brinell Hardness (BH) and embedment of the proppant into the formation. An ELE steel ball penetrometer **is** used to determine the Brinell hardness of the formation. Rock mechanics equations are used to determine the proppant embedment on one fracture face. A 0.0610-inch steel ball is used with the ELE Load Frame to penetrate the sample. The sample normally consists of a one-inch diameter cylinder with a height between 0.5 and *2* inches and containing flat end faces. One end of the sample is exposed to acid or fracturing fluid to simulate rock softening due to fluid exposure. After cleaning and drying the sample, the sample is placed on the load frame with the flat unexposed face serving as a base. After contacting the sample with the steel ball, both dials are set to zero. The applied force is increased to a minimum of 10 gauge units (GU) or 35 kg before reading the first penetration distance H in gauge units (1 GU = 0.01 mm). The applied force is then increased to 100 GU in increments of 10 or 20 GU while reading the penetration distance H. For soft rock samples; a 0.120-inch steel ball can be used. **A** spreadsheet calculates the Brinell Hardness (BH) in units of kg/mm^2 and proppant embedment (h) in units of inches or units of percent particle size. As a general rule, the percent embedment does not change as a function of particle size for a constant closure stress. Previous testing also indicates that embedment is not a problem for BH values above 50 kg/mm^2, but embedment is a problem for BH values less than about 30 kg/mm^2.

Reaction Rate Parameters Determination

Reaction Rate Parameters consist of the Reaction Rate Coefficient (k), Reaction Order (n), Reference Temperature, Activation Energy (E_a), Diffusivity and Activation Energy for the Diffusivity. These parameter values are determined by performing a series of tests using a Rotating Disk Device.

Tests include rotating a sample of the formation in different blends of acids with varying strength (7.5 **to 28% HCl**). Samples of the fluid are taken with time (1 to **10** minutes) to determine how the acid strength is changing. This is done at various temperatures **(30** to 140°F) and rotational speeds (50 to 2000 rpm). Fluid samples are analyzed using DCP (Direct Current Plasma) for the calcium concentration. Based on the reaction of HCI with limestone,

$$2HCl + CaCO_3 \rightarrow H_2O + CO_{2(g)} + CaCl_2$$

Two moles of HCI are consumed by the reaction with one mole of calcium carbonate (limestone); therefore, knowing the amount of calcium and the volume of fluid, the number of moles of calcium carbonate dissolved can be calculated, and the number of moles of HCI consumed is determined. The change in acid strength coupled with the surface area of the disk and the time is used to calculate a Flux.

$$\frac{[HCl]}{SurfaceArea \bullet Time} = u,\ \text{gmoles/cm}^2\ \text{sec} = Flux$$

Using a Diffusivity Number (D) for the acid at temperatrue a Shenvood Number (N_{Sh}) can be calculated. From this **a** Mass Transport Coefficient (K_{mt}) is calculated, and, using the Flux (u) and the Initial Concentration (C,) of acid, the surface acid concentration (C,) is calculated.

$$N_{Sh} = \frac{\nu}{D}$$

$$K_{mt} = \frac{0.62048 N_{Sh}^{-2/3}}{1 + 0.298 N_{Sh}^{-1/3} + 0.1451 N_{Sh}^{-2/3}} \bullet (\omega\nu)^{1/2}$$

$$u = K_{mt}(C_b - C_s) = K(C_s)^n$$

A log-log plot of the Flux versus the surface concentration of acid is made, and a best fit straight line calculated. The slope of the line is the Reaction Order (n), and the intercept at log surface concentration equal to one is the Reaction Rate Coefficient (K).

If sufficient core sample is available, the Diffusivity of the acid on the formation can be determined by performing the same rotational tests at various speeds. **A** plot of an F-function defined below versus the rotational speed raised to a power dependent upon the n' of the fluid results in the slope being equal to the Effective Diffusivity (Deff) raised to the 2/3 power, $(Deff)^{2/3}$. This assumes that $\mathbf{C_b >>> C_s}$ in the domain of rotational speeds where mass transport is the limiting factor to the reaction.

Newtonian Fluid

$$u = 0.62048 C_b D_{eff}^{2/3} \nu^{-1/6} \omega^{1/2}$$

Power-Law Fluid

$$u = \phi(n') D_{eff} \left({k'}/{\rho} \right)^{\frac{-1}{3(1+n')}} a^{\frac{1-n'}{3(1+n')}} C_b \omega^{\frac{1}{1+n'}}$$

F Function

$$F = \frac{u'}{\phi(n')\left(\frac{k'}{\rho}\right)^{\frac{-1}{3(1+n')}} a^{\frac{1-n'}{3(1+n')}} C_b}$$

In the equation **a** (cm) is the radius of the disk, r (g/cm^3) is the density of the fluid, **k'** (g/cm^2s^{2-n}) is the power-law consistency index and **n'** (dimensionless) is the power-law behavior index.
Where:

n'	**0.2**	**0.4**	**0.5**	**0.6**	**0.8**	**1.0**	**1.1**	**1.3**
f (n')	**0.695**	**0.662**	**0.655**	**0.647**	**0.633**	**0.620**	**0.618**	**0.604**

A plot of F versus:

$$\omega^{\frac{1}{1+n'}}$$

can be analyzed for that range of rotational speeds where mass transport controls the reaction limit and the range where surface reaction is the limiting factor.

CASE HISTORIES

Case History No.1

A West Texas limestone reservoir was evaluated for keys to achieving an effective stimulation with acid. Rocks are **94%** to **98%** calcite, <1% to 3% quartz, and 1% - 2% ferroan dolomite. SEM examination reveals that much of the porosity is microporosity; however, microfractures are present in the rock (Figure 1). Rock porosities range from 0.2% to 5.8%, and permeabilities range from 0.05 md to 2.2 md. To improve productivity from the limestone, fracture stimulation will be necessary.

To facilitate an effective stimulation samples of the rock were examined for hardness before and after exposure to acid, to understand whether the rock will maintain its integrity after acid stimulation, **Table 1.** The rock retains approximately 57% of its initial strength after exposure to acid. In addition, the rock surface was examined for differential etching, **Figure 2.** From this evaluation, it was determined that multiple viscosity fluids were not needed to achieve effective conductivity. Since the formation is made up of two different lithologies (Chert and Limestone) an understanding of the reactivity of these two materials was valuable in determining the effectiveness of penetration of different acid blends. **Table 2,** lists a comparison of reaction rate parameters determined. From this data it was determined that a gelled or crosslinked acid system would be adequate to achieve adequate retardation. It was also determined that viscous acids alone would provide acceptable leak-off control.

Treatments performed prior to this evaluation employed large gelled water and large neat or in-situ crosslinked acids, **Table 3.** Total volumes of fluids used on these wells ranged from 300000 to 600000 gallons and required 20% and 28% HCI. **Table 4,** lists the treatment varieties since the study. The volumes of fluid used in the treatments were reduced approximately 30% to 78% with treatment costs being reduced approximately **40%** to 80%. In addition, 15% HCl was used effectively. Production responses comparing the average daily production rate after three months of production and the first year's cumulative production are also listed in **Tables 3 and 4.** These show that oil and gas production was as good or in most cases significantly better using the smaller treatments (70 to 200%).

Case History No.2

In the Middle East, a formation consisting of a sequence of limestone and dolomite was characterized in a similar fashion to Case History 1. These particular wells were new, with a bottom hole temperatures of 270" to 290°F. An understanding of the reservoir and stimulation options to provide the best production response was essential.

Limestones are 84% to **94%** calcite, with **4%** to **14%** mineral dolomite. Anhydrite (calcium sulfate) is present (Tr – 5%). Strontium sulfate was detected in one sample. Dolostones are **84%** to 98% mineral dolomite. One sample contained some calcite (1%) and one sample contained abundant anhydrite (15%).

Core samples were evaluated for rock mechanical properties, **Tables 5 and 6.** Young's Modulus and Poisson's Ratio, along with a correlation of values that could be determined from open-hole logs, were determined. In addition, the hardness before and after acidizing was evaluated, and a theoretical conductivity was determined, **Table 7.** Strengths were reduced from approximately 22 to 63%. The Theoretical Conductivity based on an assumed closure pressure of 6000 psi ranged from 30.3 md-ft to 63.5 md-ft. Pictures of the rock surfaces before and after acidizing are illustrated in **Figure 3.** It can be seen that the surface of the fractured dolostone which contained anhydrite was most significantly affected. Finally the reactivity of different acid blends on the rock was determined and parameters for use in an Acid Fracturing Model calculated, **Table 8.** A graphical representation of the change in Reaction Rate Coefficient with respect to the inverse of the absolute temperature for three fluids on the most reactive of the limestone sections is presented in **Figure 4.** This shows that gelled acid or crosslinked HCI acid have a similar reactivity on the limestone, while the neat acid reaction rate is soaring.

Treatments performed to date included multiple stages of crosslinked gelled water and in-situ crosslinked 28% HCl, **Table 9.** This is in contrast to Case History No. 1 above because of leak-off problems. Production responses after clean-up of treating fluids, of these wells are reported in **Table 10.** Three of the wells were tested after perforating and before the stimulation. Responses of 63% improvement to a five fold increase were observed.

Case History No. 3
North Sea carbonates are hard chalks and consist of 93% to 97% calcite, 2% to 7% quartz, and minor quantities of halite (NaCl) and sylvite (KCI). Rocks of potentially productive intervals are very fine grained and microporosity is the principal porosity type. Stylolite development has occurred.

As in the above case histories evaluation of the formations ability to be etched in a differential manner and maintain integrity were evaluated, **Table 11.** The strength of the formation sample evaluated was reduced the least of formations evaluated recently, only a 4.5% reduction was observed. A theoretical conductivity of 221.1 md-ft was also calculated assuming a closure of 6000 psi. Photographs of the before and after effects on the surface are in **Figure 5.** It can be seen that the surface is fairly smooth and it was recommended that multiple fluid strengths or viscosity be used to enhance a differential etching. **Also,** the parameters useful in comparing penetration and/or reactivity of acid blends were determined, **Table 12.** Again it can be observed that a ten fold reduction in reaction can be achieved with a gelled or crosslinked HCl blend.

A treatment **(Table 13)** developed as **a** result of this work consisted of either multiple stages of a crosslinked and gelled HCI acid and crosslinked gelled water. The typical scheme for treating this formation consist in using alternate stages of in-situ crosslinked HCI acid in place of the gelled and crosslinked acid. In all cases, a final stage of neat acid was used to achieve near wellbore conductivity

.Production response information is limited as the well was produced for a few days at 15,000 bopd and then, as planned, was turned into an injector. The zone is accepting 37,000 bwpd at 5000 psi. The well will be evaluated using PLT analyses methods on an injector to determine the effectiveness of stimulation of each zone.

CONCLUSIONS

I. Understanding rock composition, rock mechanical properties, acid etching patterns, and the morphology of the pore system enhances the design of acid treatments.
2. Treatments carefully designed and using laboratory generated parameters provided greater stimulation than did previous treatments.

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Table 1
Hardness Information Before and After Acidizing

Before	After
99533	56567

Table 2
Reaction Rate Parameters For use in Meyers Acid Fracturing Design Program
For West Texas Limestone

Parameters	**values of Reaction Rate Parameters**			
	Rock Sample			
	Limestone/Chert	**Limestone**	**Limestone**	**Limestone**
Fluid Tested	**Crosslinked Acid**	Neat **Acid**	**Gelled Acid**	**Crosslinked Acid**
Acid Specific Gravity	1.0545	1.0545	1.0545	1.0545
Acid Molecular Weight	36.47	36.47	36.47	36.47
Dissolving Power	1.37	1.37	1.37	1.37
Reaction Rate Coefficient	2.45E-05	1.71E-04	2.91E-05	1.81E-05
Reaction Order	0.677	0.390	0.563	0.424
Activation Energy	7.33	6.54	3.67	3.27
Reference Temperature	338.7	338.7	338.7	338.7

Stages	Typical Treatments	Typical Treatment Rate, BPM	Typical Treating Pressure, psi	Typical Treatment Costs. thousands $	Average Production Rate after Three Months	Cumulative Production after First Year
I	160000 gals. Gelled Water Pad 180000 gals. 28% HCI	50	6800	350	36 BOPD, 659 MCFD	6127 BO. 166 MMCF
2	130000 gals. Gelled Water Pad 125000 gals. 28% HCI	35	6300	270		
	or					
I	40000 gals. Crosslinked Gelled Water 100000 gals. In situ Crosslinked HCI 30000 gals. 20% HCI	75	5400	375	17 BOPD, 374 MCFD	4790 BO, 128 MMCFD
2	50000 gals. Crosslinked Gelled Water 70000 gals. In situ Crosslinked HCI 20000 gals. 20% HCI	SO	6000	270		

Table 4
Typical Treatments and Results on West Texas Limestone After Reservoir Review and Evaluation

Stages	Typical Treatments	Typical Treatment Rate, BPM	Typical Treating Pressure, psi	Typical Treatment Costs, thousands $	Typical Production Response: Average Production Rate after Three Months	Typical Production Response: Cumulative Production after First Year
1	83000 gals. Slick 20% HCl	60	6150	125	34.6 BOPD, 1.123 MMCFD	10600 BO. 343 MMCFD
	or					
	112500 gals. Slick 15% HCl	80	4350	115		
2	41500 gals. Slick, Gelled or Crosslinked 20% HCl	55	5000	84		
	or					
	94000 gals. Slick or Gelled 15% HCl	85	5550	122		
	or					
Single	156000 gals. Slick 15%HCl	88	5300	161	32 BOPD, 1.036 MMCFD	7099 BO, 373 MMCFD

Table 5
Rock Mechanical Properties of Middle Eastern Carbonate

Lithology	Young's Modulus, x 10^3	Poisson's Ratio
Limestone	**2.2**	**.360**
Limestone	**1.32**	**.271**
Lime/Dolomite	**3.33**	**.275**
Dolomite	**1.64**	**.338**
Dolomite	**2.32**	**.230**
Lithology	Young's Modulus, x 10^3	Poisson's Ratio
Limestone	**4.97**	**.283**
Limestone	**3.96**	**.291**
Lime/Dolomite	**6.34**	**.279**
Dolomite	**3.30**	**.214**
Dolomite	**7.34**	**.306**

Table 6 Ultrasonic Wave Velocities for Middle Eastern Carbonate					
Lithology	**Bulk Density g/cc**	**P-wave Velocity (ft/s)**	**S-wave Velocity (ft/s)**	**Inverse P-wave Velocity (μsec/ft)**	**Inverse S-wave Velocity (μsec/ft)**
Limestone	2.373	14141	7781	71	129
Limestone	2.342	12846	6972	78	144
Lime/Dolomite	2.634	15087	8351	66	120
Dolomite	2.317	10928	6586	92	153
Dolomite	2.747	16458	8693	61	115

Table 7 Hardness Information Before and After Acidizing on Middle Eastern Carbonate Formation			
	Rock Embedment Strength, psi		**Theoretical Conductivity', md-ft**
Lithology	**Before**	***After***	
Limestone	70425	50784	63.5
Limestone	51072	31494	30.3
Lime/Dolomite	59041	39040	42.5
Dolomite	62027	49324	60.2
Dolomite	129988	47647	55.6

' Calculations based on a closure pressure of 6000 psi using method of Nierode and

Table 8				
Parameters	Values of Reaction Rate Parameters			
	Rock Sample			
	Limestone	Limestone	Limestone	Dolomite
Fluid Tested	Neat HCl Acid	Gelled HCl Acid	Crosslinked HCl Acid	Neat HCl Acid
Reaction Rate Coefficient	3.85E-05	4.3E-06	4.28E-06	1.81E-05
Reaction Order	0.680	0.190	0.270	0.700
Activation Energy	7.00	3.75	2.27	11.7
Reference Temperature	338.7	338.7	338.7	338.7

Table 9
Typical Acid Fracture Treatment Schedule Middle Eastern Carbonate

Stage	Fluid Description	Volume
Pre-Pad	40 pptg Linear Gelled Water	9000
Pad	40 pptg Crosslinked Guar Gelled Water	15000
Acid	In-Situ Crosslinked 28% HCl Acid	14000
Pad	40 pptg Crosslinked Guar Gelled Water	9000
Acid[1]	In-Situ Crosslinked 28% HCl Acid	14000
Pad	40 pptg Crosslinked Guar Gelled Water	9000
Acid	In-Situ Crosslinked 28% HCl Acid	12000
Overflush	40 pptg Linear Gelled Water	9000
Acid[2]	Neat 28% HCl Acid	10000
Flush	40 pptg Linear Gelled Water	9500

Average Treating Rate 55 BPM
Average Treating Pressure 9400 psi

[1] Increase Rate to Maintain Pressure above Closure.
[2] Reduce Rate to allow acid to increase near wellbore conductivity.

Table 10		
Well	Before Stimulation	After Stimulation
1	N/A	18.2 MMCFD
2	8.5 MMCFD	33 MMCFD
3	27 MMCFD	44 MMCFD
4	7 MMCFD	43 MMCFD

Rock Embedment Strength, psi		
Before	After	Theoretical Conductivity', md-ft.
60120	57431	221.1

Table 12
Reaction Rate Parameters For use in Meyers Acid Fracturing Design Program For North Sea Limestone

Parameter	Neat HCI Acid	Slick HCI Acid	Crosslinked HCl
Reaction Rate Coefficient	8.05E-05	2.46E-06	3.12E-06
Reaction Order	0.461	0.337	0.191
Activation Energy	1.46	1.64	1.09
Reference Temperature	338.7	338.7	338.7
Effective Diffusivity	6.23E-05	1.27E-07	1.77E-07

Table 13
North Sea Carbonate Treatment Variances

Treatments for Two Zones		
Stage	**Fluid Description**	**Volumes, Bbls**
Pad	40 pptg Crosslinked Guar Gelled Water	450
Acid – 1	Crosslinked 15% HCl	700
Acid – 2	Gelled 15% HCl	20
Acid – 3	Neat 15% HCl	30
Overflush	40 pptg Linear Gelled Water	-------
Treatments for 16 Zones		
Stage	**Fluid Description**	**Volumes, Bbls**
Pad	40 pptg Crosslinked Guar Gelled Water	450 to 900
Acid – 1	In-situ Crosslinked 15% HCl	195 to 1500
Acid – 3	Neat 15% to 28% HCl	30
Overflush	40 pptg Linear Gelled Water	-------

Figure 1 – Scanning Electron Micrograph of the West Texas Reservoir, Showing the Fine Grained Texture of the Rock, Minimal Visible Porosity, and a Possible Natural Fracture (Upper Right Corner) - Original Magniciation = 80x Corne

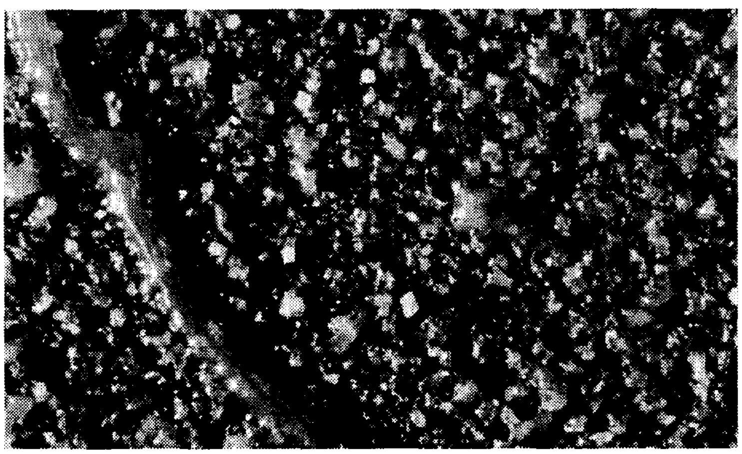

Figure 2 - The etched surface of the West Texas reservoir rock shows a hummocky appearance. Relief is the result of differential etching and may be dependent on grain size

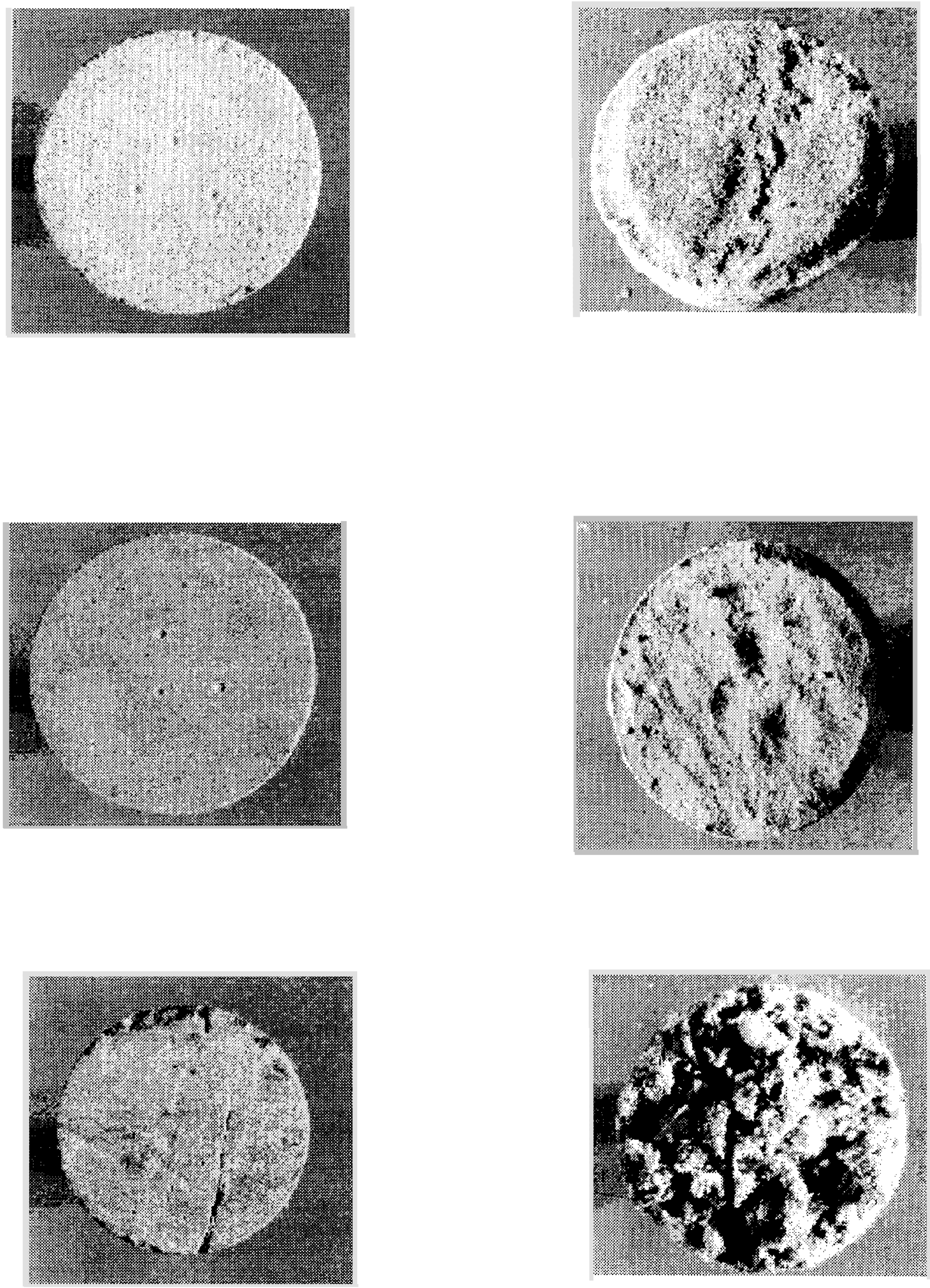

Figure 3. Before (Left) and After (Right) Examples of Etched Surfaces from the Middle East Study Area - The top pair of photos are of a limestone, the middle pair of photos depicts a dolostone lithology, and the bottom pair of photos depicts a fracture, anhydritic dolostone. Isolated surface highs in the middle photos are probably due to the presence of small amount of quartz and anhydrite. Note that the limestone exhibits a good differential etch pattern.

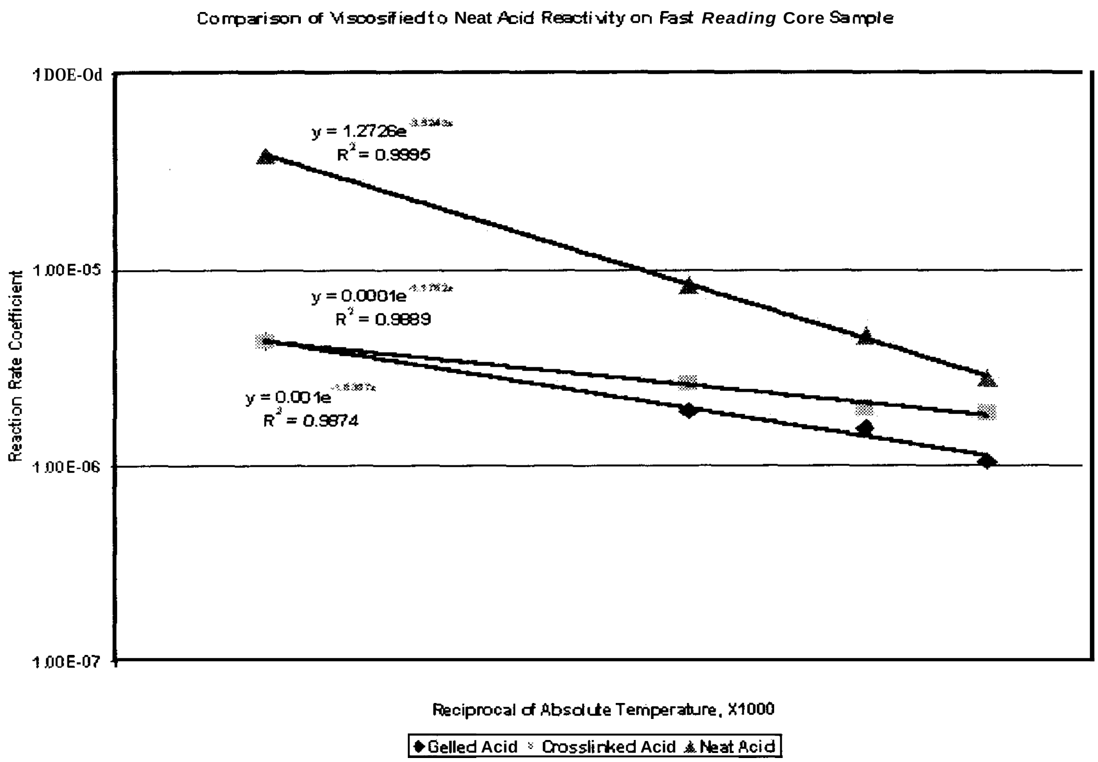

Figure 4 - Plots of Reaction Rate Versus the Reciprocal of Temperature (Absolute) for Neat, Gelled and Crosslinked (XLA-III) Hydrochloric Acid Reacted on Core Samples of Middle Eastern Limestone - The equation for the exponential trend of the data and the statistical coefficient are included. The resultant parameters are listed in **Table 8.**

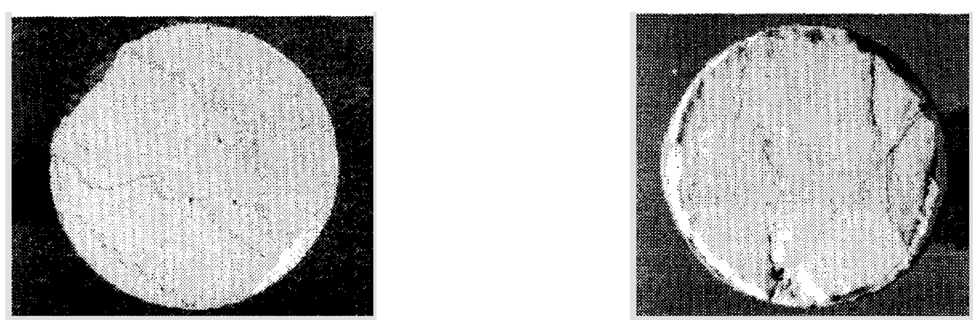

Figure 5 - Stylolites (black irregular lines) are evident in the North Sea chalk sample. The sample is hard and dense. The etched plug (right) exhibits relief along stylolite surfaces. Usually bitumen or clay is concentrated along these pressure solution features.