WAVEX®, Inc.

Monitoring Water Contacts

Using Pressure and Flowrate Measurement

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    "See All of the Limits, All of the Time."
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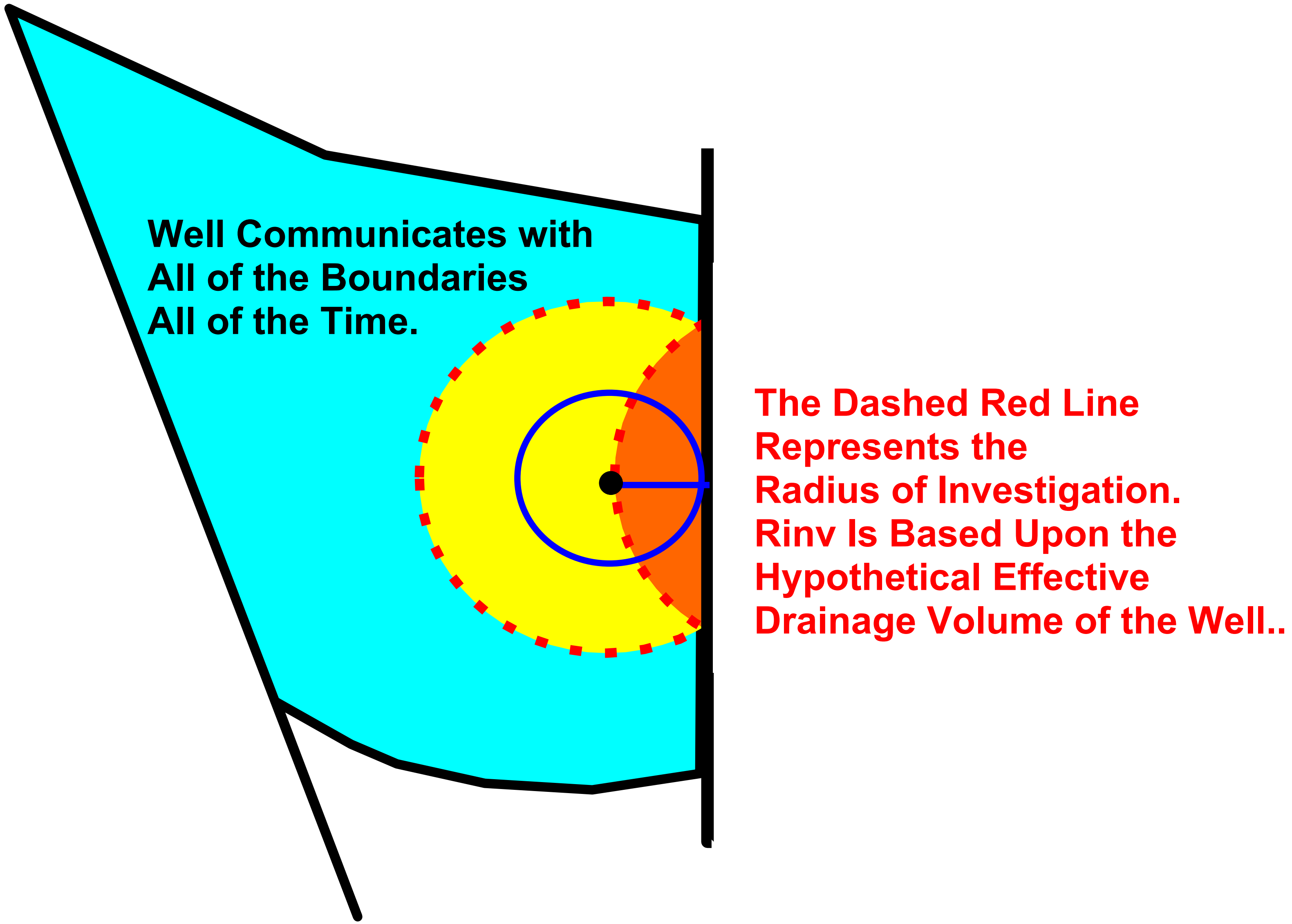
    "See One Limit at a Time."
- **WAVEX®** Processing:
  - **Problem Breakdown**
  - **Example**
  - **Logic: Teaching a Completion to Observe**
- The History of Change

Pressure Transient Analysis

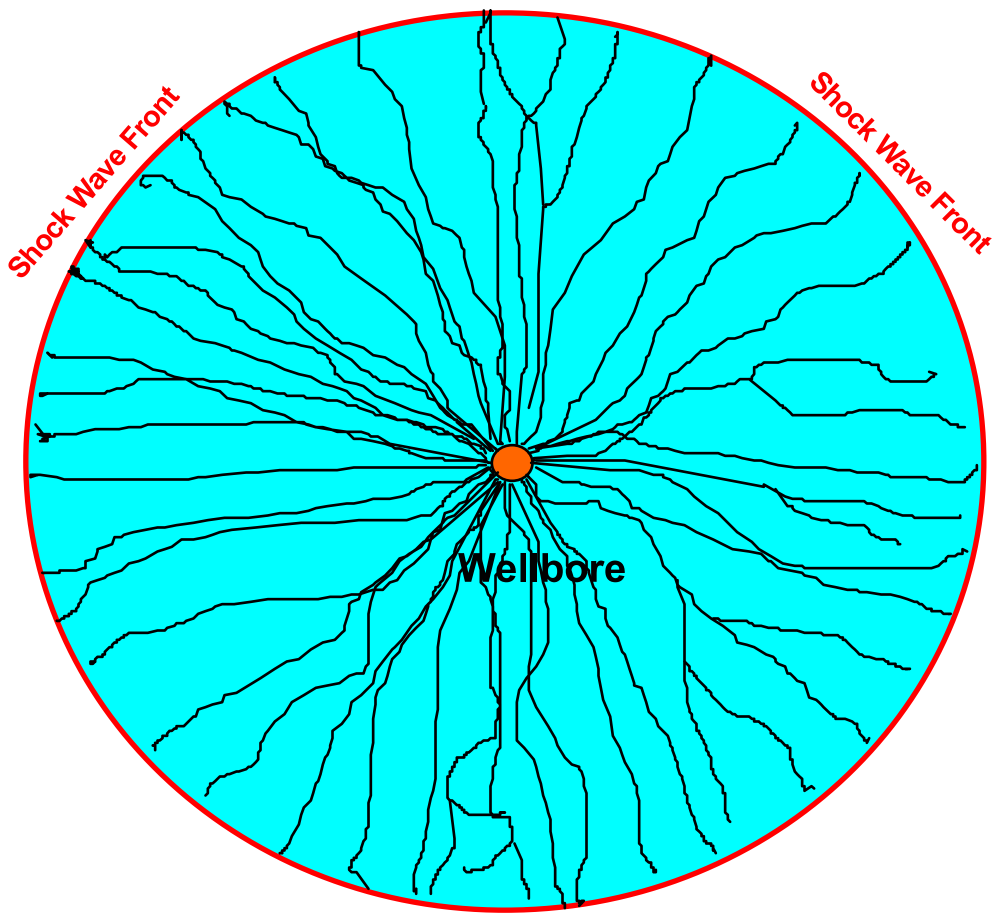
Determining Reservoir Properties and Boundaries by Analyzing Pressure Changes in the Reservoir that Result from a Production Rate Change.


Well Communicates with
All of the Boundaries
All of the Time.
The Dashed Red Line
Represents the
Radius of Investigation.
Rinv Is Based Upon the
Hypothetical Effective
Drainage Volume of the Well..

WaveX® Technology

- Uses Advanced **Wave Mechanics** Model
- Detects Each Limit's **Shape** and **Distance**
- Directly Measures Reservoir **Volume**
- Dimensionally Confirms **Mapped Geology**

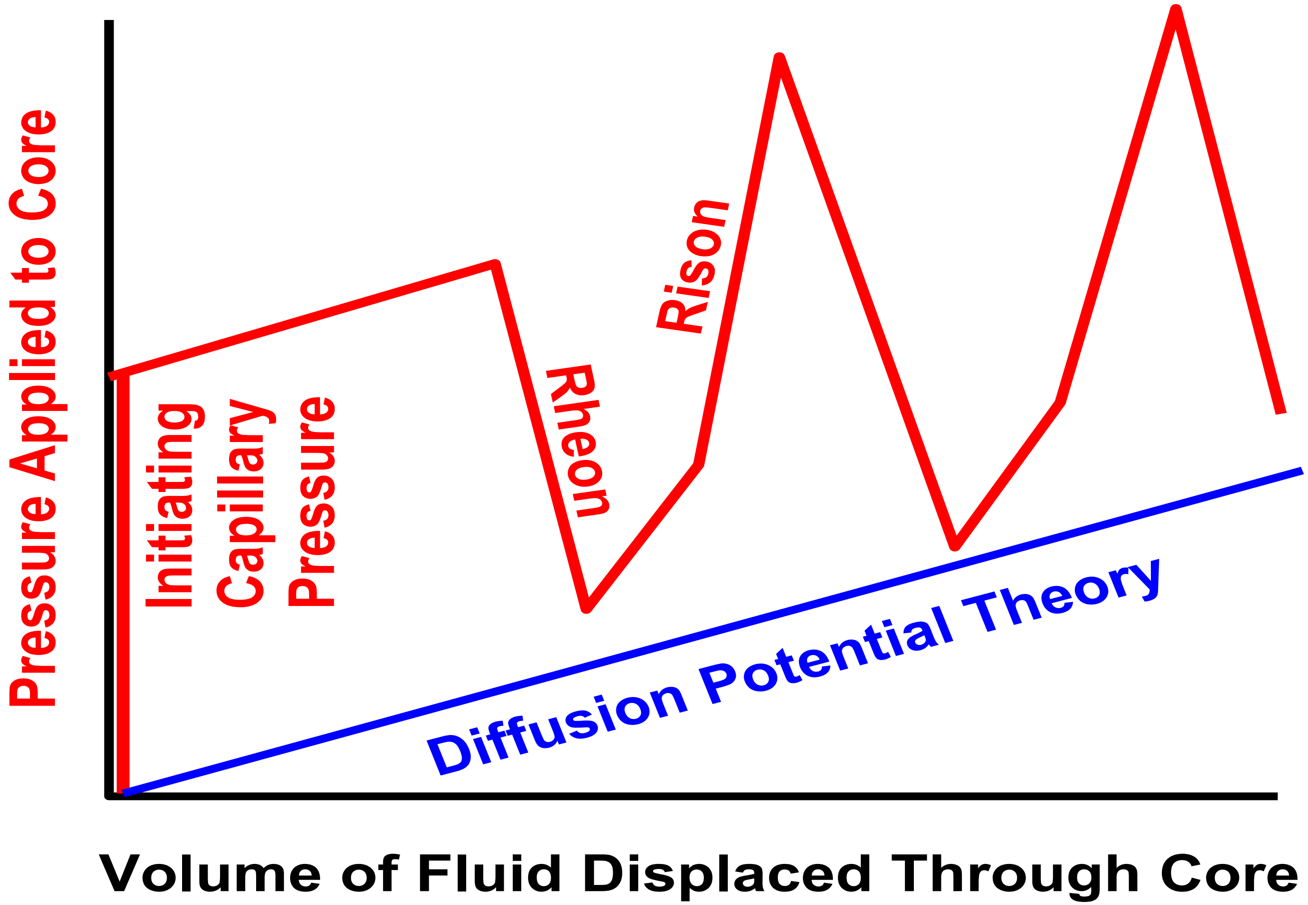
Clusters of Growing Capillaries



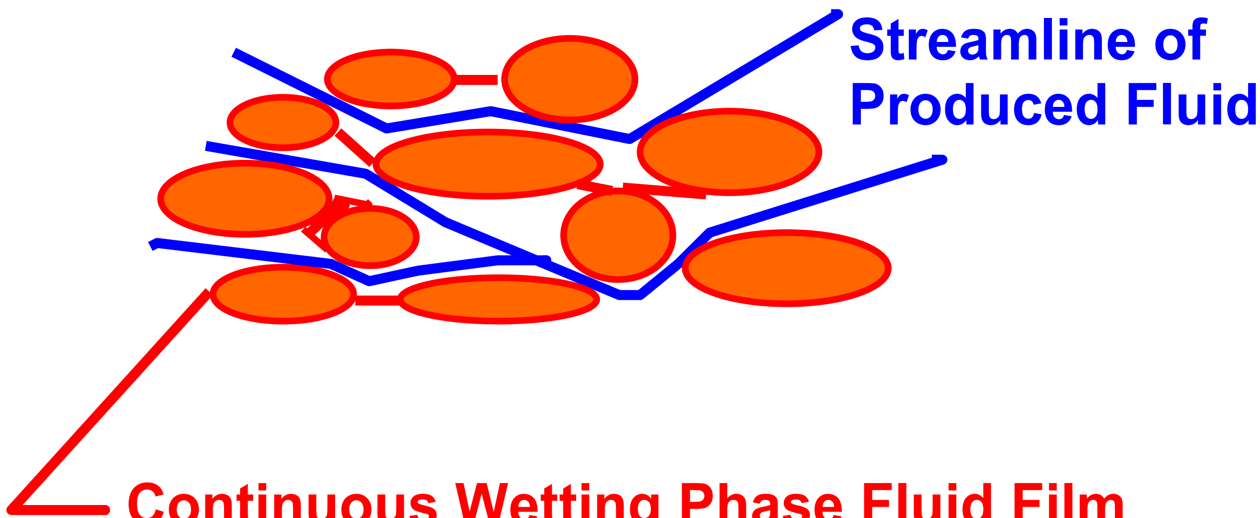
Capillaries Open One Pore Throat at a Time

- Potential Flow Model Proposed by Hurst in 1933.
- By 1940 Haines Discovered:
  - Capillary Entry Pressure and
  - Haines Jumps
- By 1960's Jones Publishes Dichotomy in Theoretical Distance to First Limit.

Flow Through a Core as Observed in the Laboratory

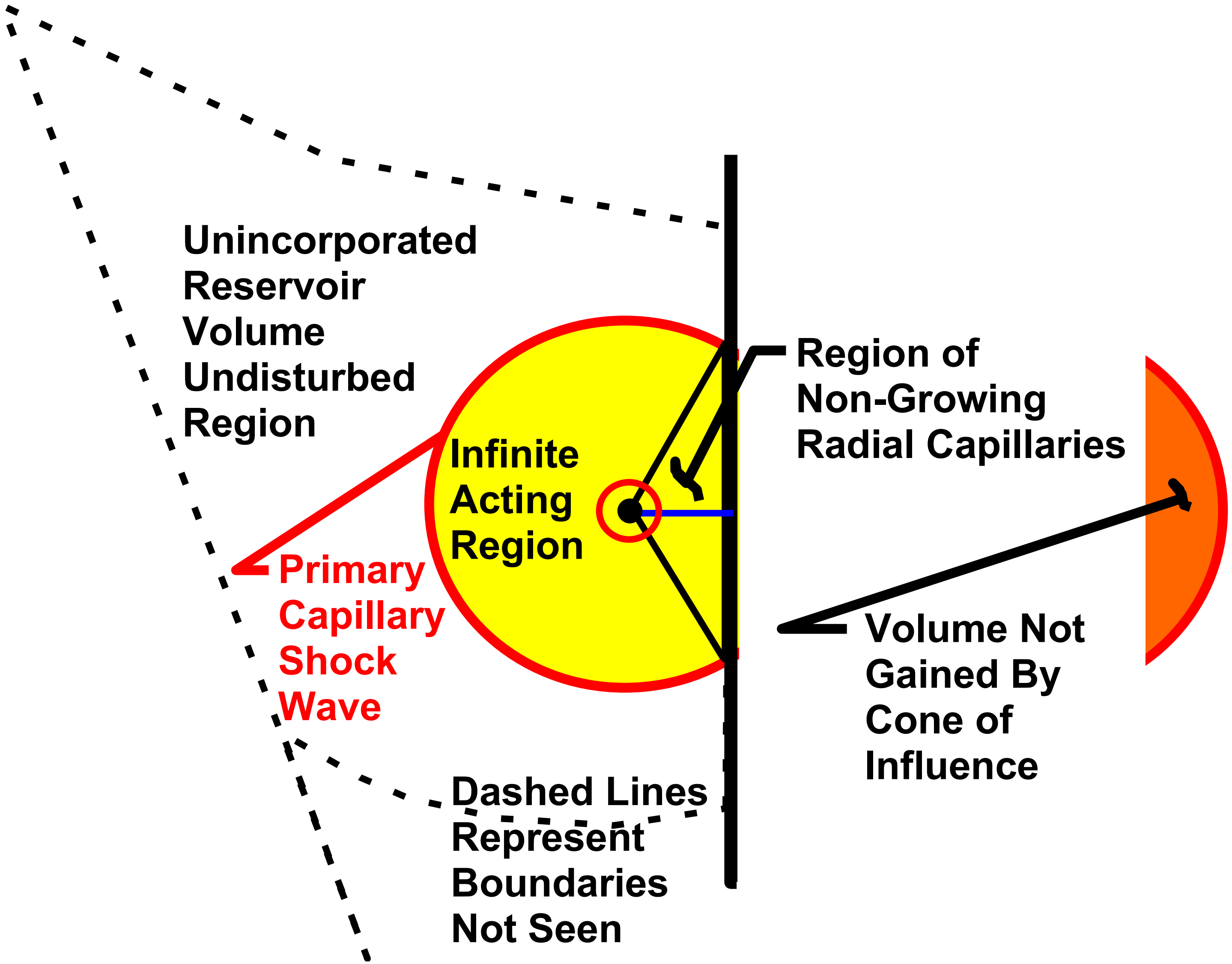


Capillary Paths Stabilize as Entry Pressure Is Overcome



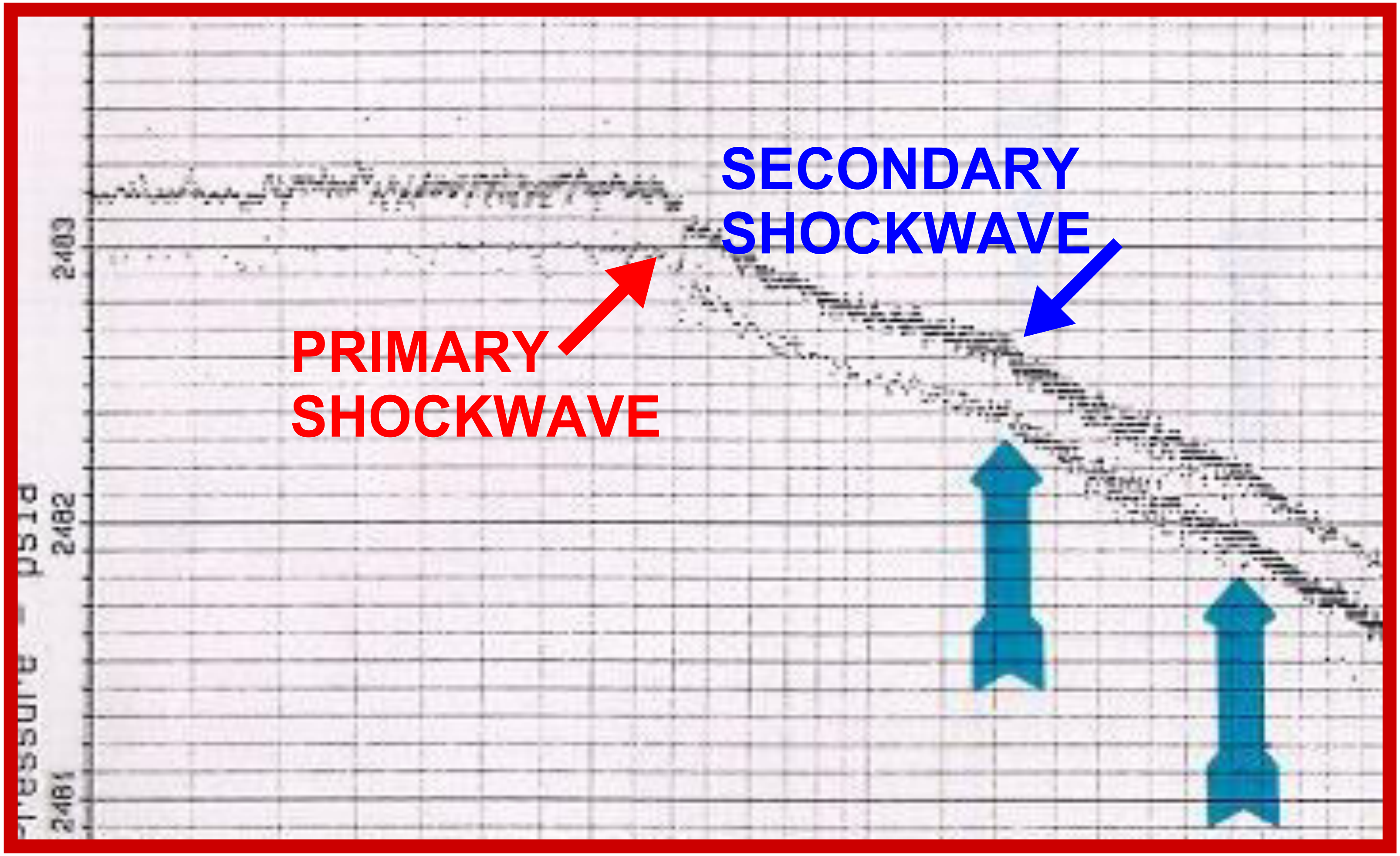
To Break the Fluid Film in Order
to Allow a Change in Flow Path,
Requires a Finite
Initiating Differential Pressure
Across any Pore Throat.

WaveX® Model

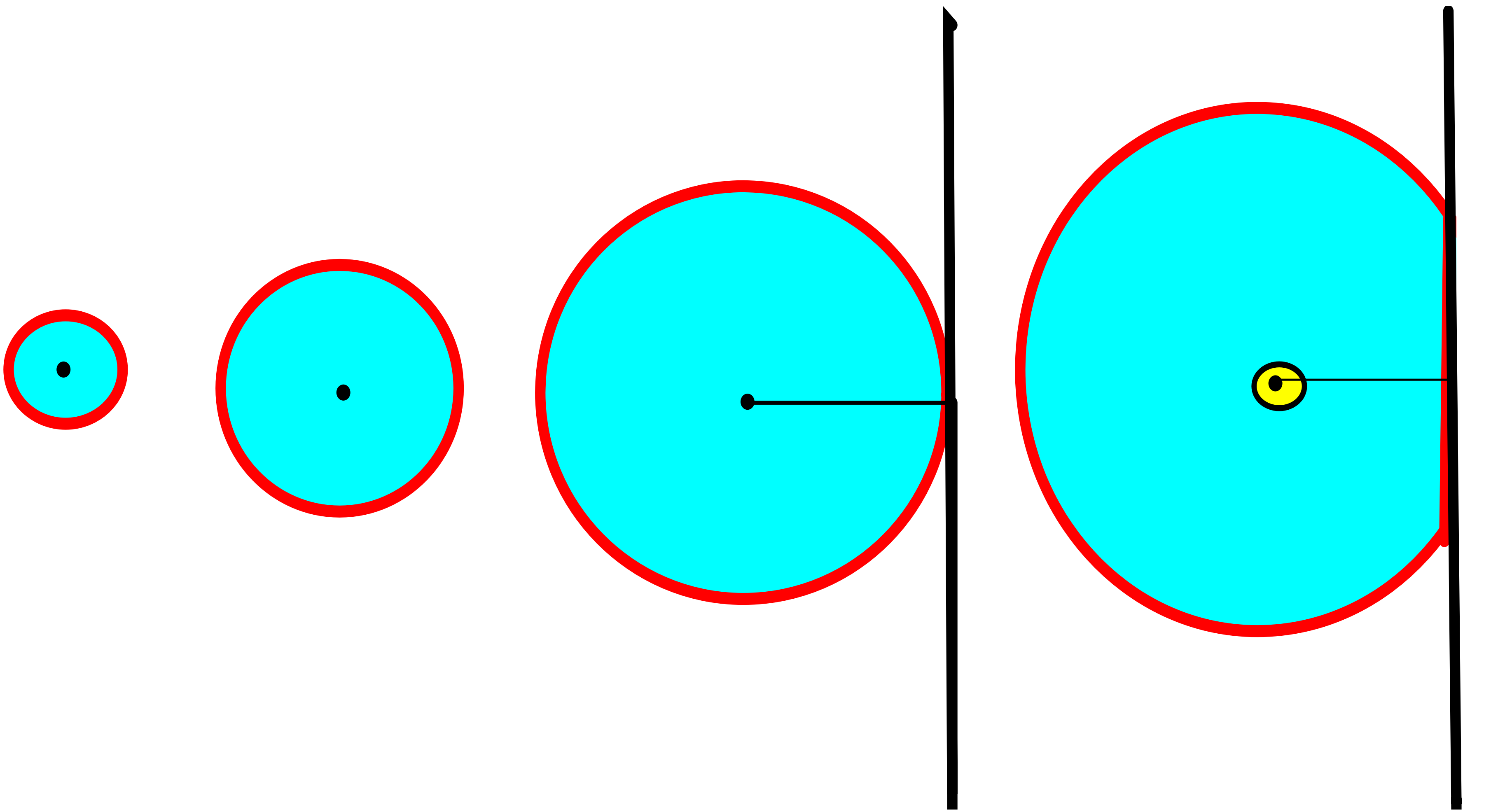


Unincorporated
Reservoir
Volume
Undisturbed
Region
Infinite
Acting
Region
Region of
Non-Growing
Radial Capillaries
Primary
Capillary
Shock
Wave
Volume Not
Gained By
Cone of
Influence
Dashed Lines
Represent
Boundaries
Not Seen

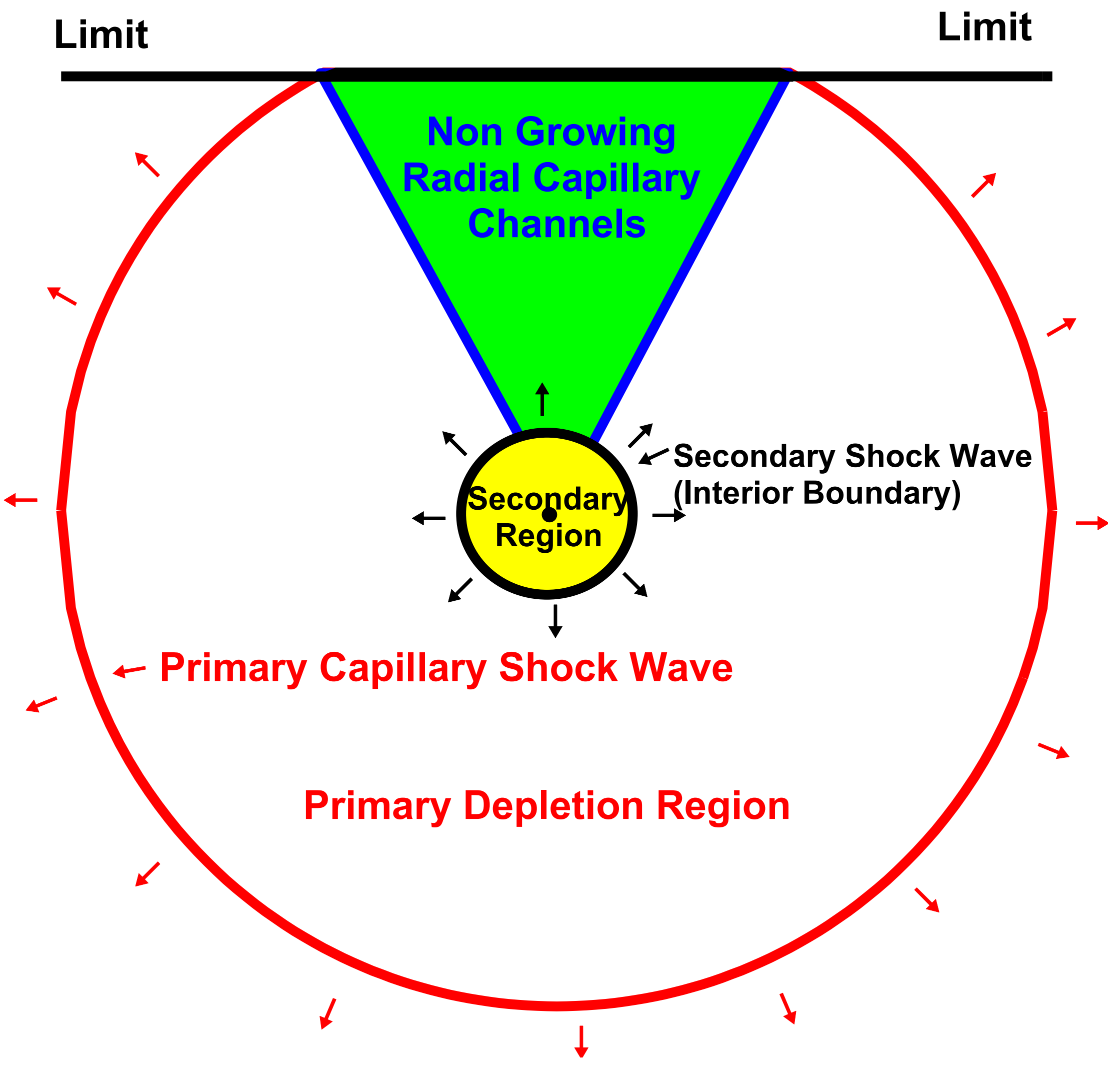
When the Primary Shockwave Hits a Limit, It Reproduces.



Growth Process for a Cone of Influence



Cone of Influence and Limit



WaveX® Concept Summary

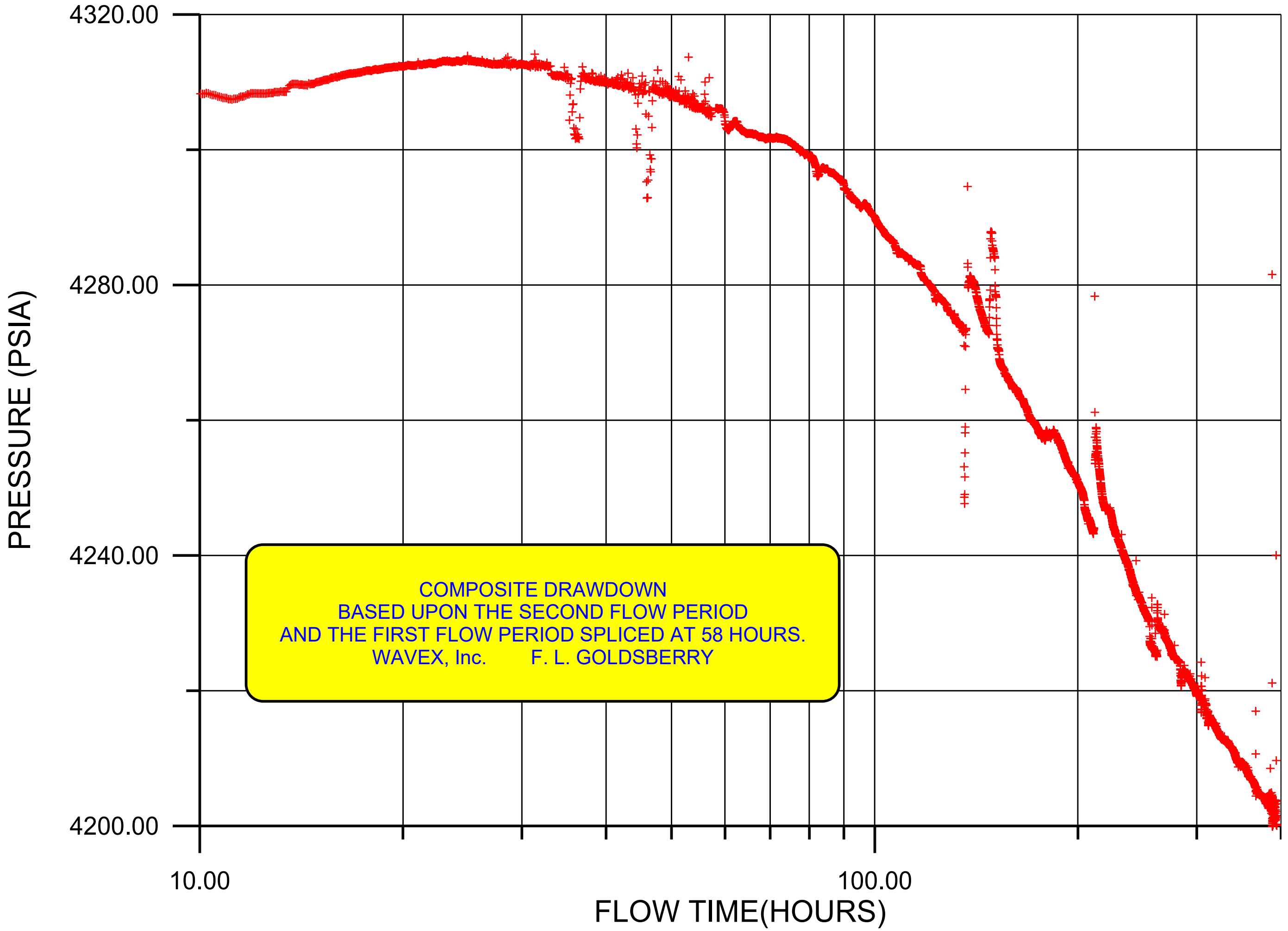
- **The Circular Capillary Wave Represents a "*Bubble*" of Constant Hydraulic Power Dissipation that Grows Radially and Is Constrained by Initiating Capillary Pressure Electronic Membrains that Exist at the Pore Throats Along the Original Stream Lines and Whose Path of Flow Is Stabilized by Fluid Inertia.**
- **The Secondary Waves and Their Bounded Regions Must Follow the Same Laws.**

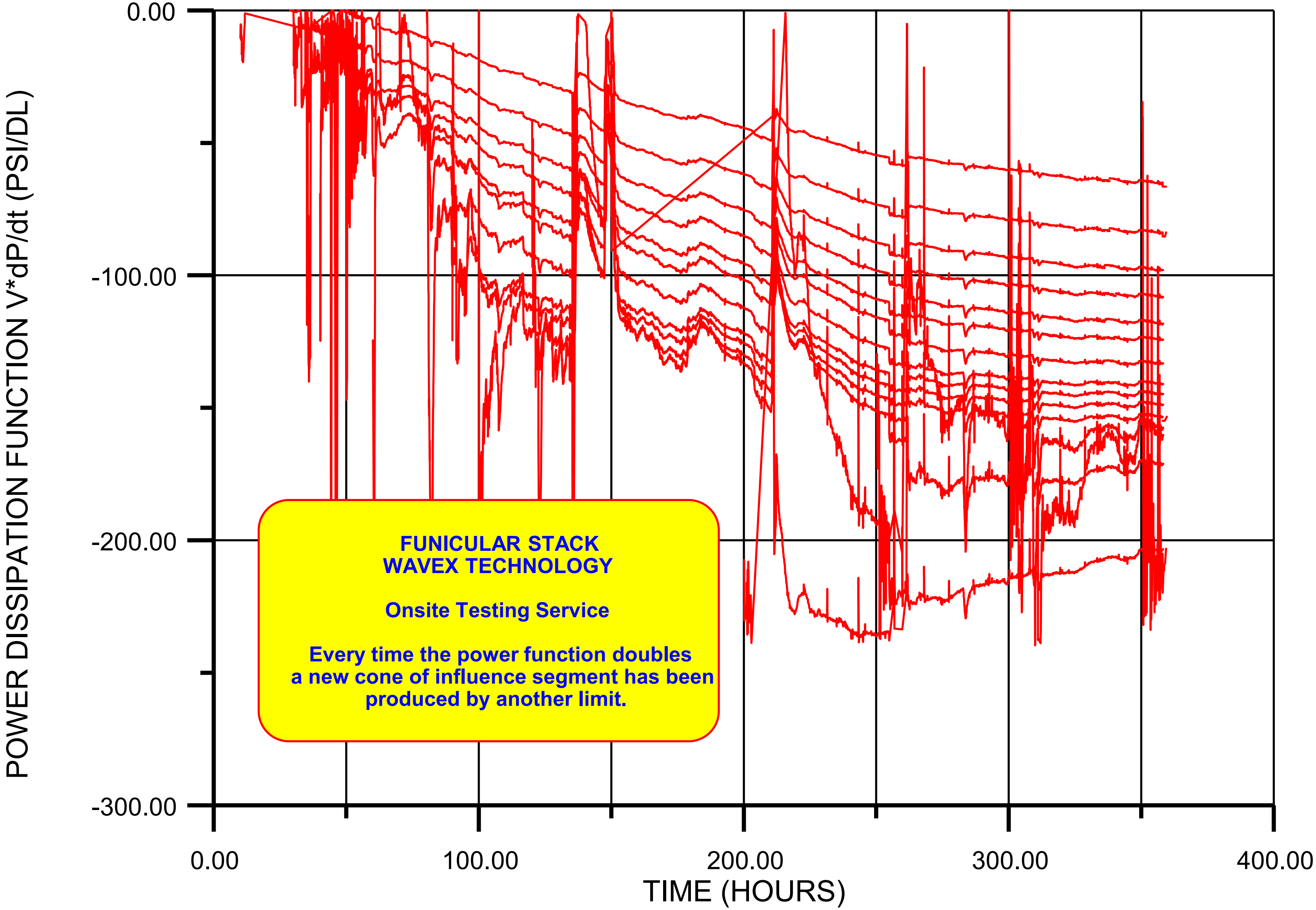
4D Map Logic

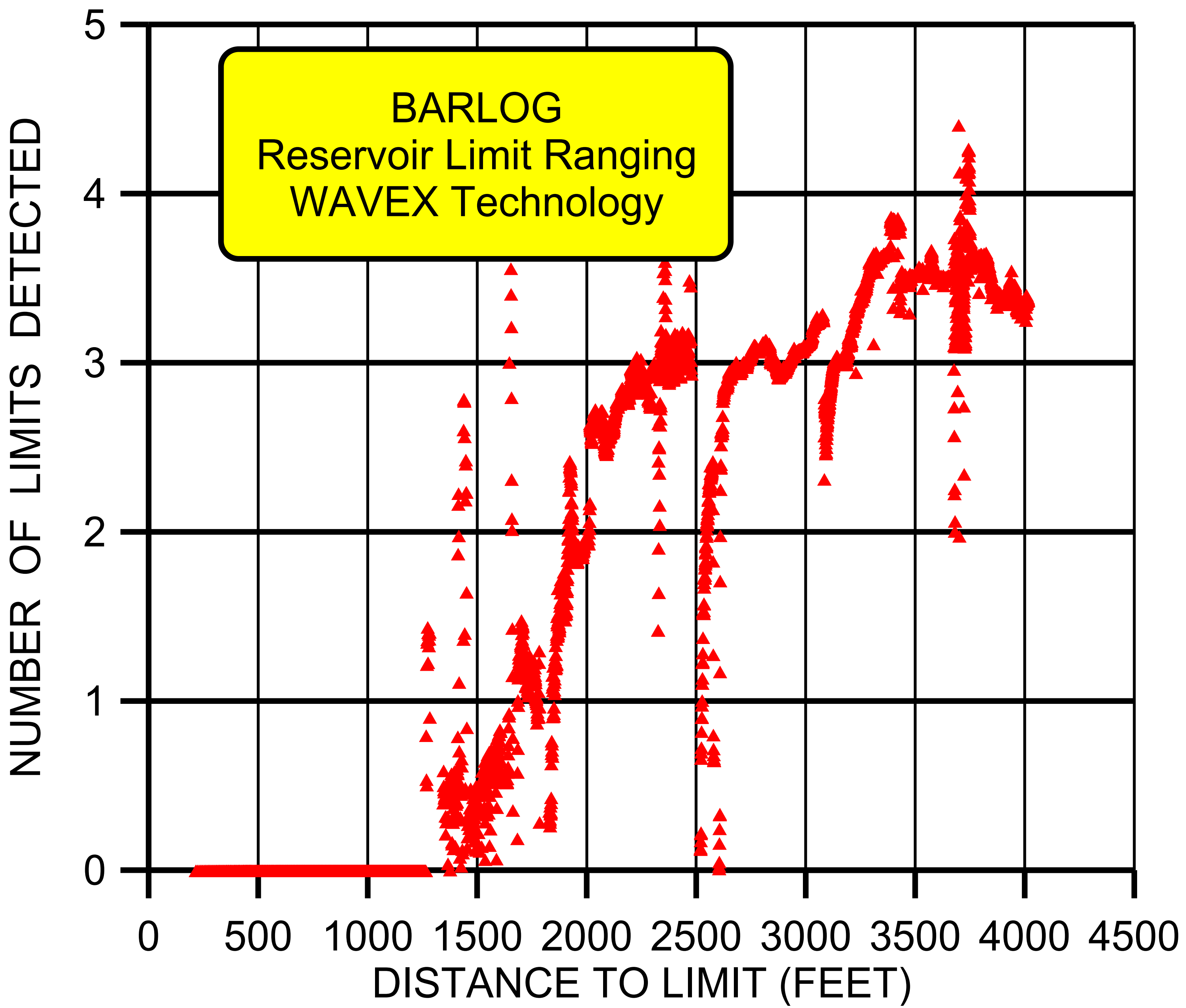
- Pressure Log Initially to Map Each Limit Individually as to
  - Distance
  - Shape
- Everytime the Well Shuts In, BARLOG™ (Pressure Log) Again to Detect a Water Leg.
- If a Limit Moves, It Must Be the Water Contact.
- Remap at Every Shut In Opportunity.

WAVEX® Process Steps

- *Straight Line Sections are Identified on a SemiLog Pressure Plot.*
- *Pressure Slope Shifts and Times are Input to Computer.*
- *Direct Calculations Are Made for:*
  - *Distance to Limit*
  - *Shape of Limit* **Deflection Angle from Straight Line**
  - *Volume* **Integral Material Balance**
- *Computed Limits Are Map Overlaid or Oriented "Blind".*


4320.00
4280.00
4240.00
4200.00
PRESSURE (PSIA)
10.00
100.00
FLOW TIME(HOURS)
COMPOSITE DRAWDOWN
BASED UPON THE SECOND FLOW PERIOD
AND THE FIRST FLOW PERIOD SPLICED AT 58 HOURS.
WAVEX, Inc. F. L. GOLDSBERRY

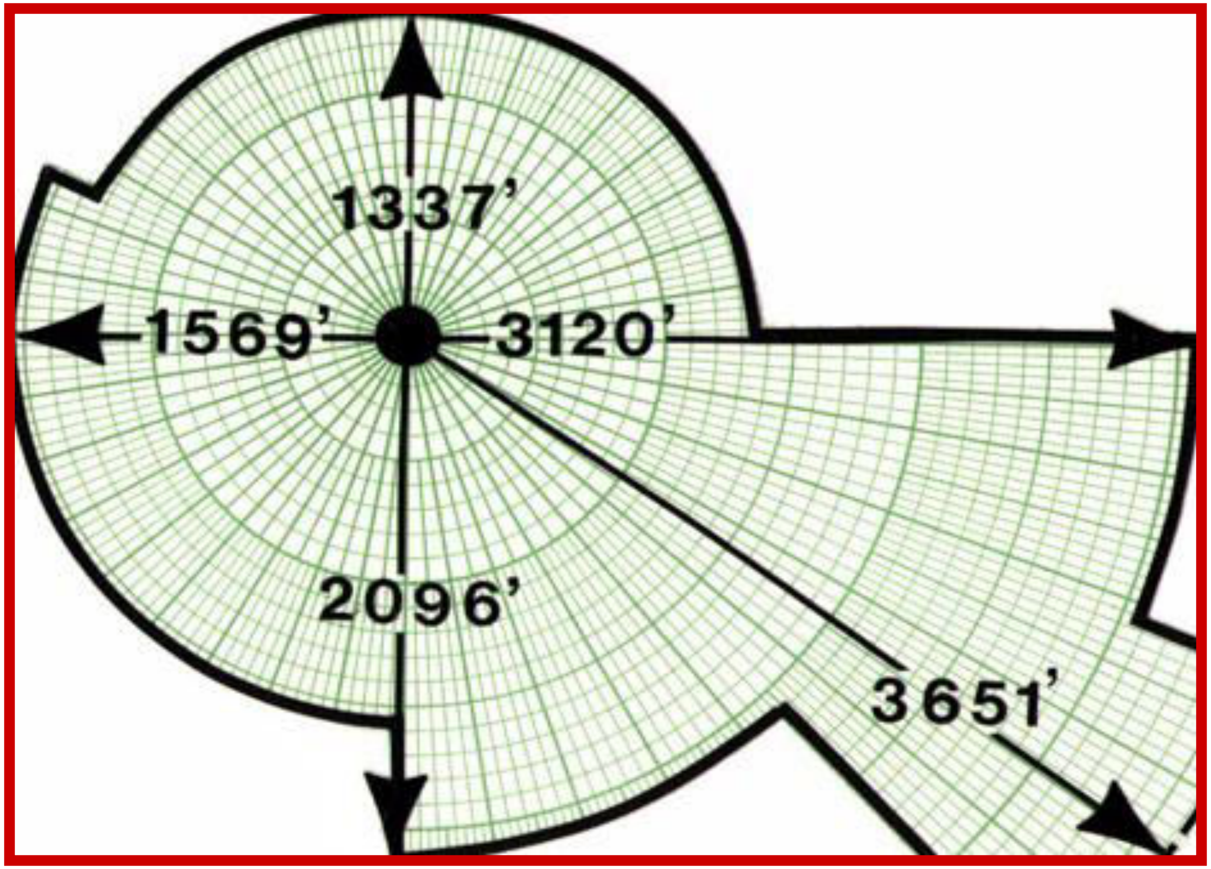

0.00
-100.00
-200.00
-300.00
POWER DISSIPATION FUNCTION V*dP/dt (PSI/DL)
0.00
100.00
200.00
300.00
400.00
TIME (HOURS)
FUNICULAR STACK
WAVEX TECHNOLOGY
Onsite Testing Service
Every time the power function doubles
a new cone of influence segment has been
produced by another limit.


BARLOG
Reservoir Limit Ranging
WAVEX Technology
NUMBER OF LIMITS DETECTED
0
1
2
3
4
5
0
500
1000
1500
2000
2500
3000
3500
4000
4500
DISTANCE TO LIMIT (FEET)

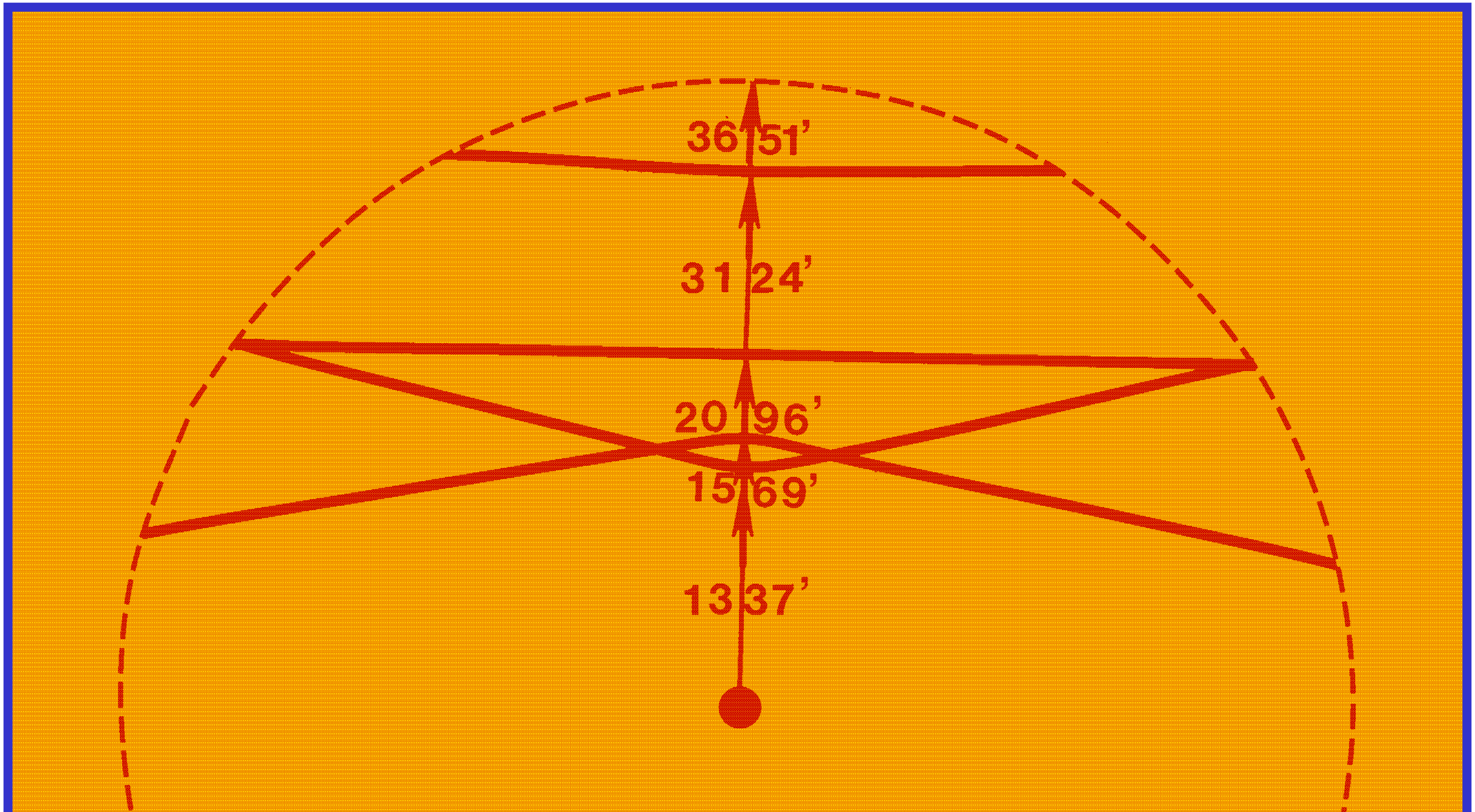
Reservoir Volume Explored

Test Time Integral of Apparent Volume
Gained by Cone of Influence During the Test

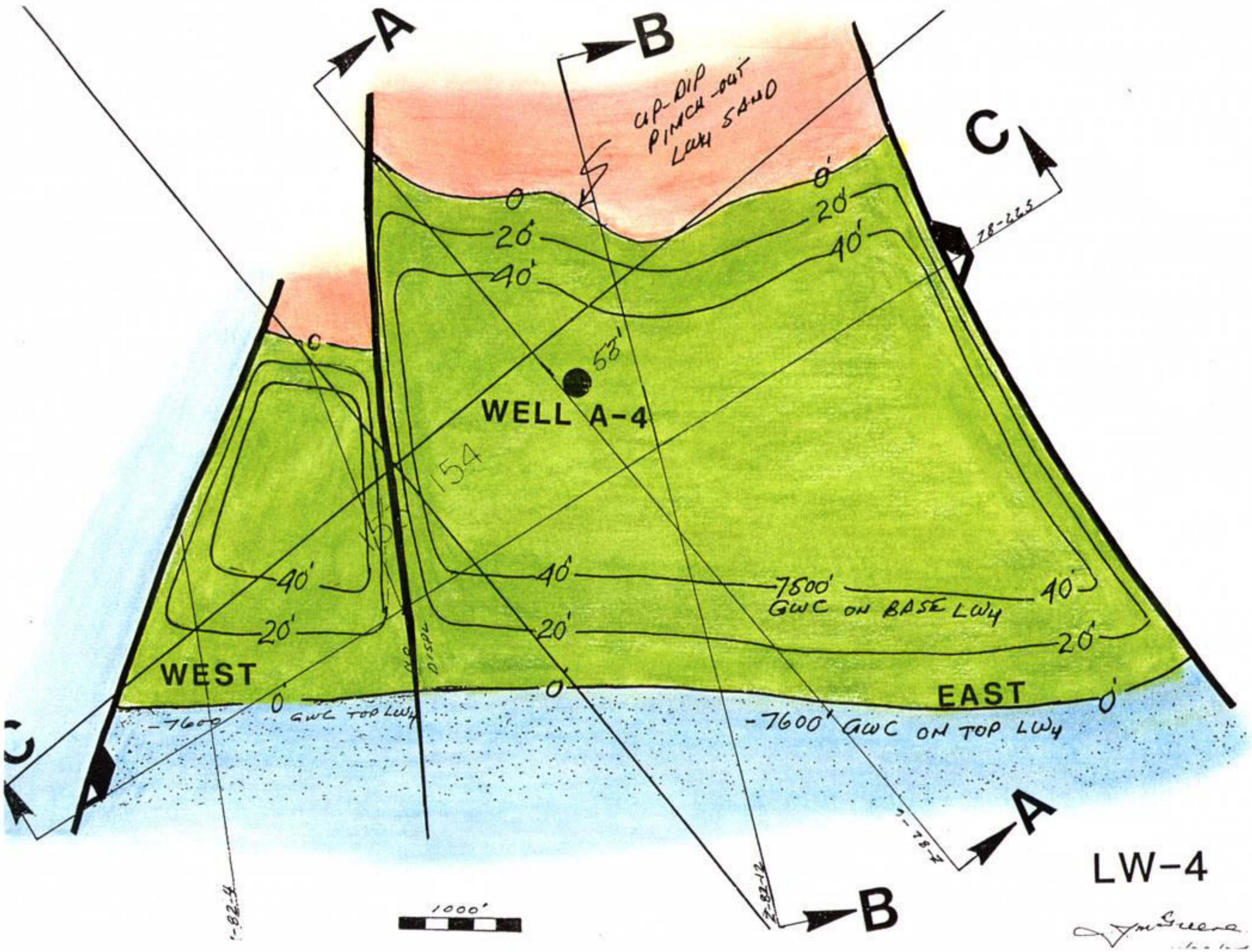
WaveX® Tangent Diagram Map

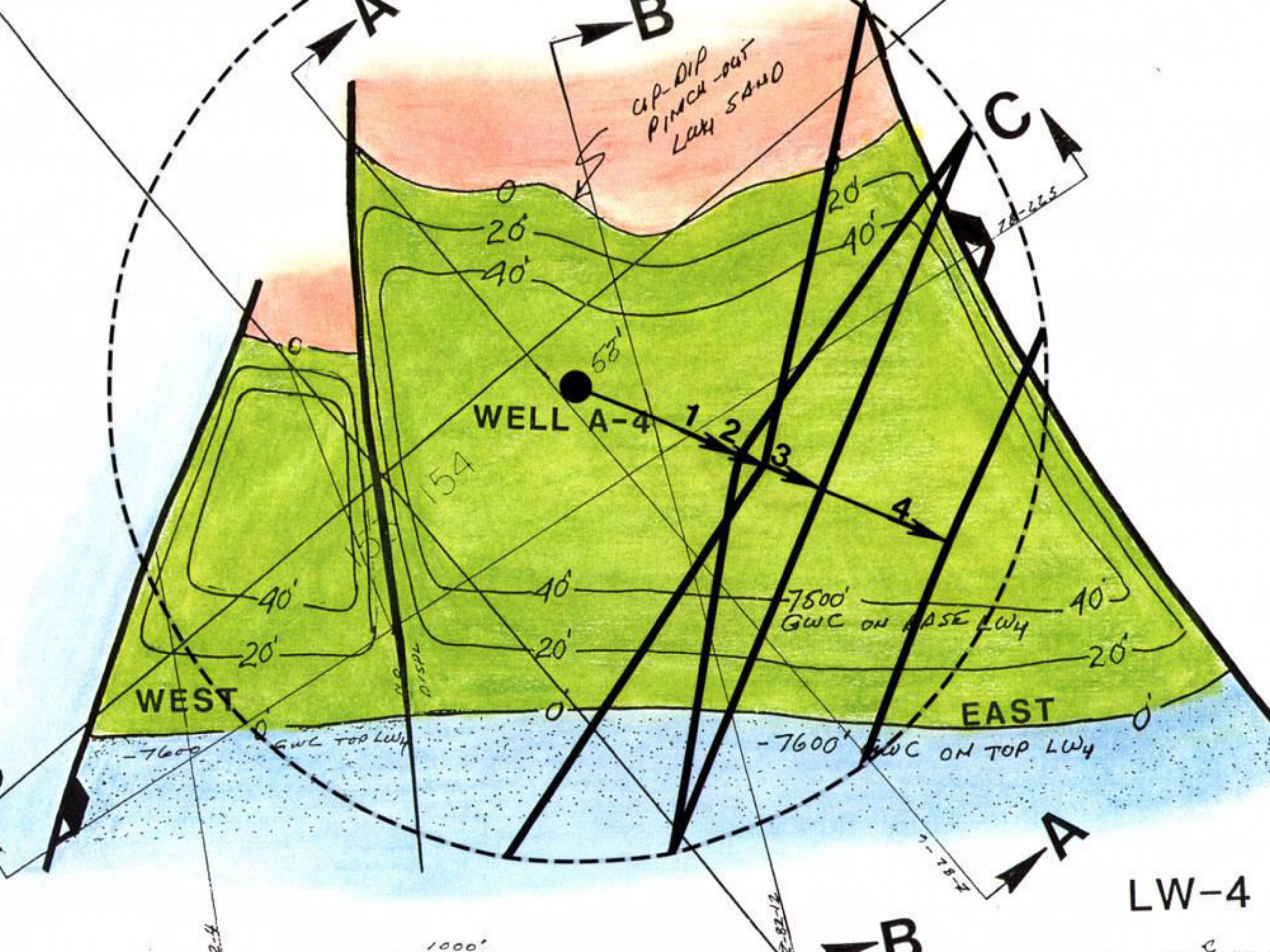


WaveX® Limit Diagram



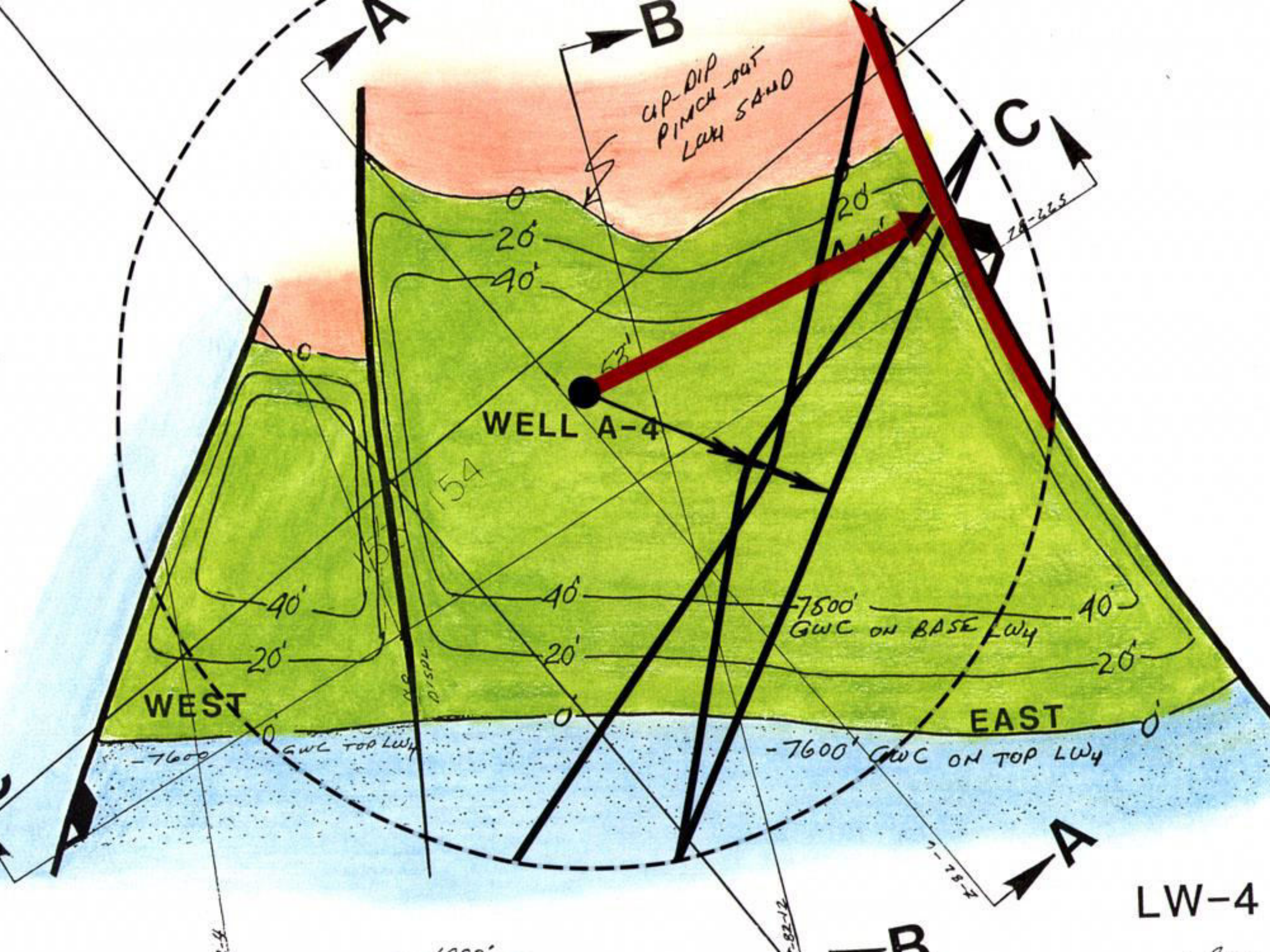
Results Compared to the Geologists Map



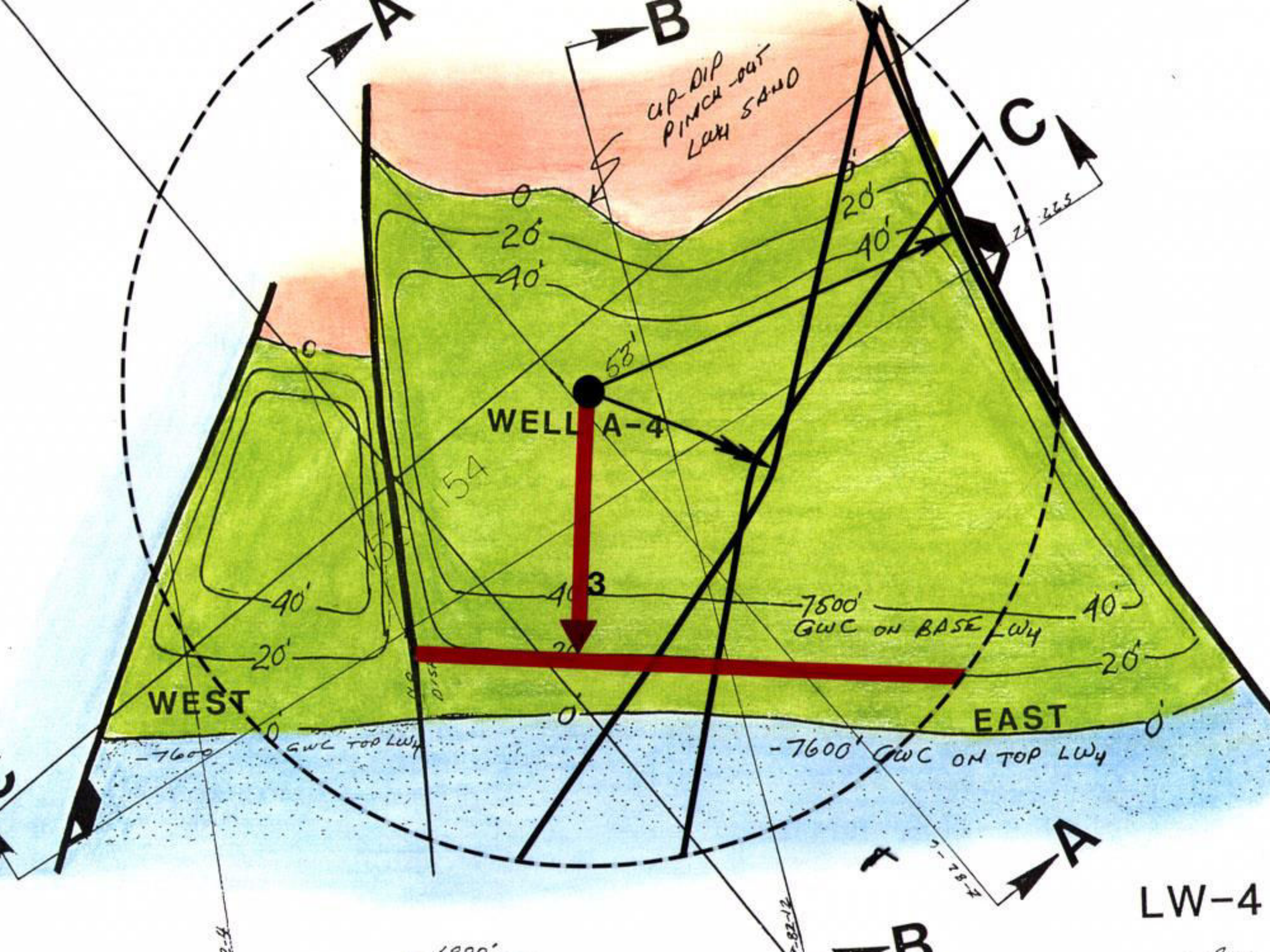


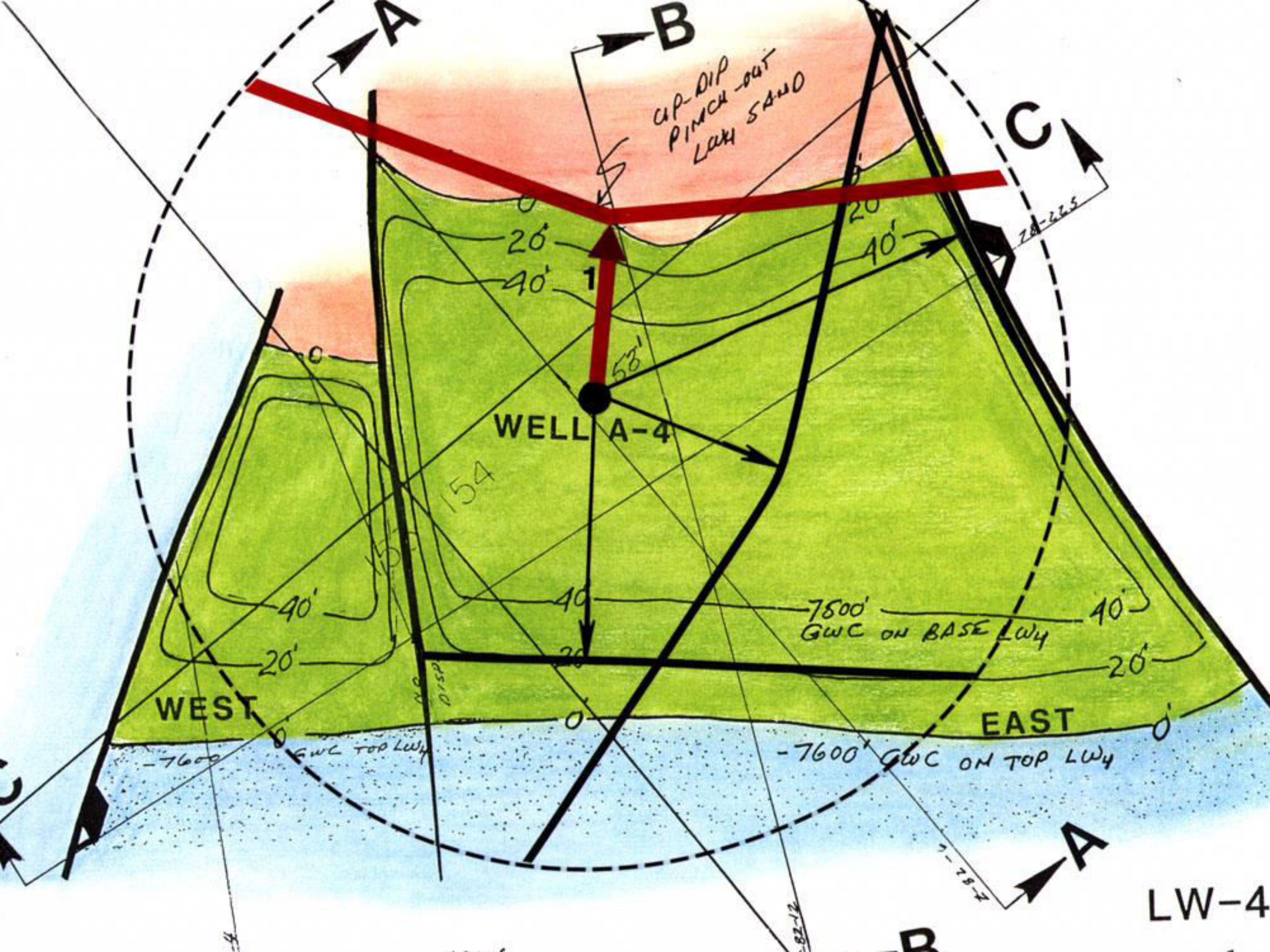
A
B
C
UP-DIP PINCH-OUT LW4 SAND
0
20'
40'
58'
WELL A-4
1
2
3
4
154
DISPL
-7600' GWC ON BASE LW4
WEST
EAST
-7600 GWC TOP LW4
-7600' GWC ON TOP LW4
1000'

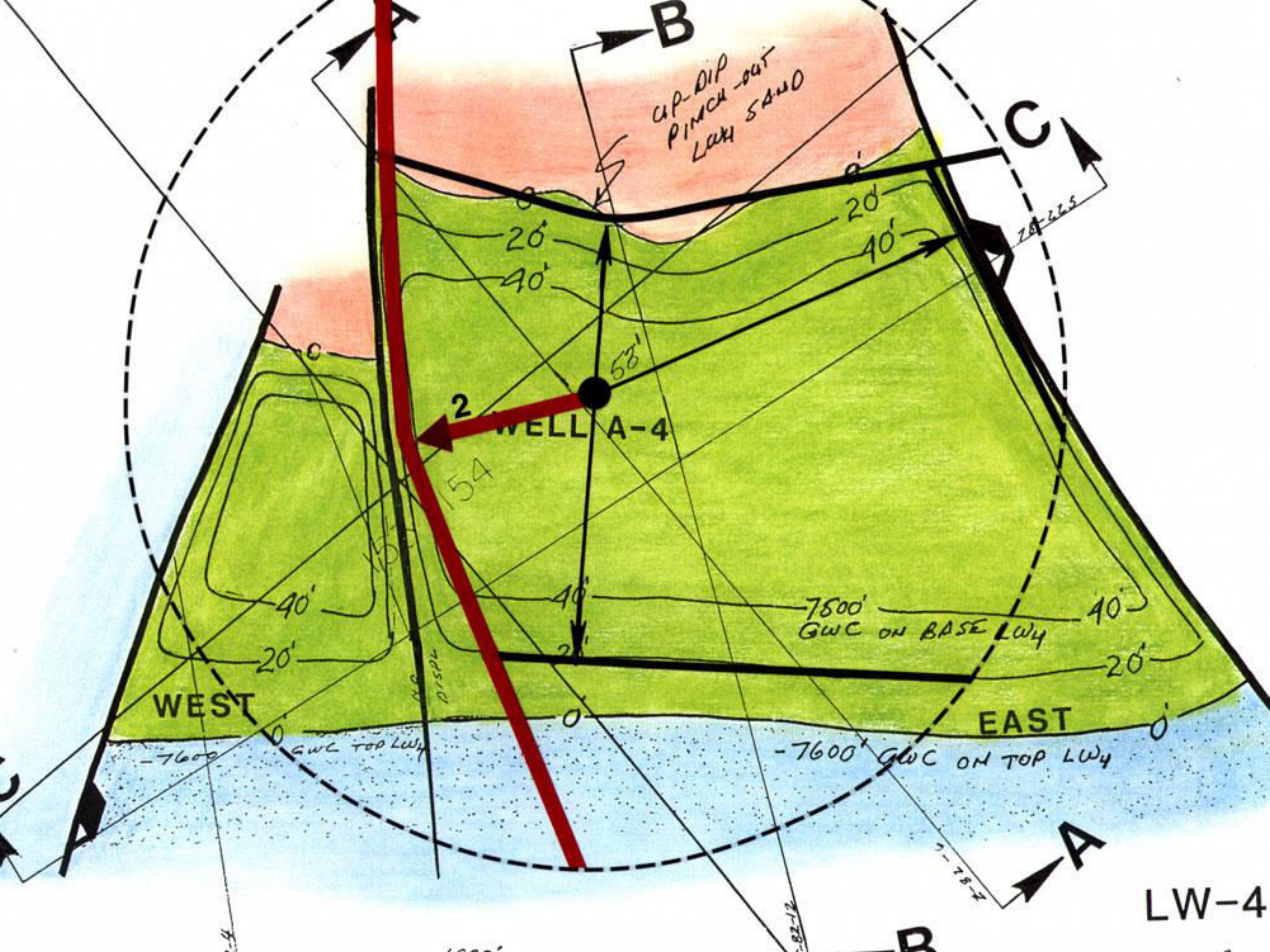
LW-4



A
B
C
UP-DIP PINCH-OUT LW4 SAND
WELL A-4
154
WEST
EAST
0
20'
40'
-7600' GWC ON BASE LW4
-7600' GWC ON TOP LW4
-7600 GWC TOP LW4
LW-4


A
B
C
UP-DIP PINCH-OUT LW4 SAND
0
20'
40'
58'
WELL A-4
154
3
-7600' GWC ON BASE LW4
WEST
EAST
-7600 GWC TOP LW4
-7600' GWC ON TOP LW4
LW-4


A
B
C
UP-DIP PINCH-OUT LW4 SAND
1
53'
WELL A-4
154
0
20'
40'
-7800' GWC ON BASE LW4
WEST
EAST
-7600 GWC TOP LW4
-7600' GWC ON TOP LW4
LW-4



A
B
C
UP-DIP PINCH-OUT LW4 SAND
WELL A-4
2
58'
0'
20'
40'
-7600' GWC ON BASE LW4
WEST
EAST
-7600' GWC ON TOP LW4
GWC TOP LW4

LW-4

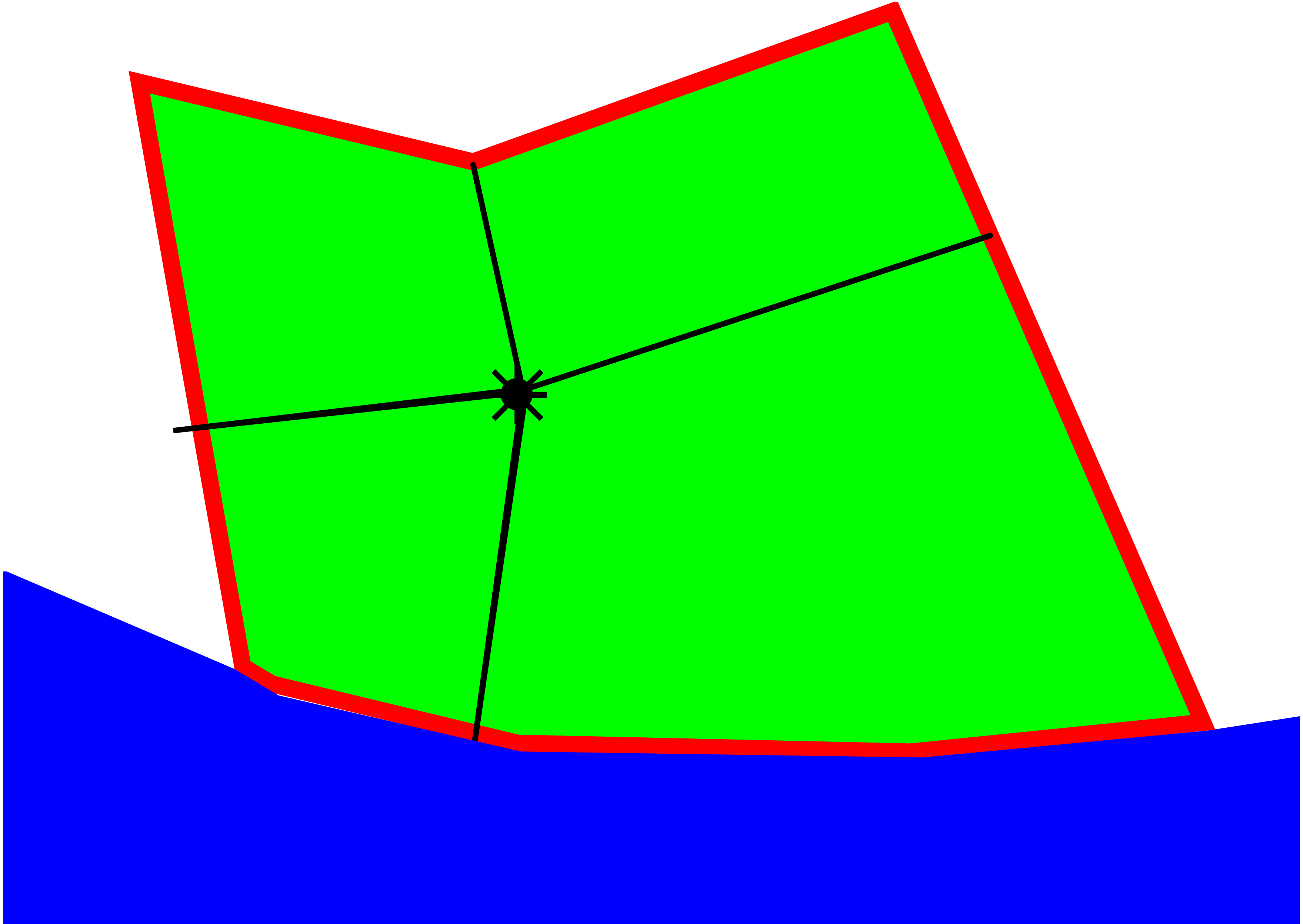
The Well "*See's*" Limits Using Pressure, Rate and Time… No Map Data is Required.

- The Well Completion Identifies Discrete Limits Using Data From Flow Periods and Buildups.
- It Recognizes Changes in Limit Relationships.
- The Well Can Logically Track the Approach of a Gas/Water or Gas/Oil Contact.
- The Well Can Be Preprogrammed to Shut In If…
  - **The Contact Moves Too Rapidly**
  - **The Contact Moves Too Close**
  - **As Fluid Hits the Well**

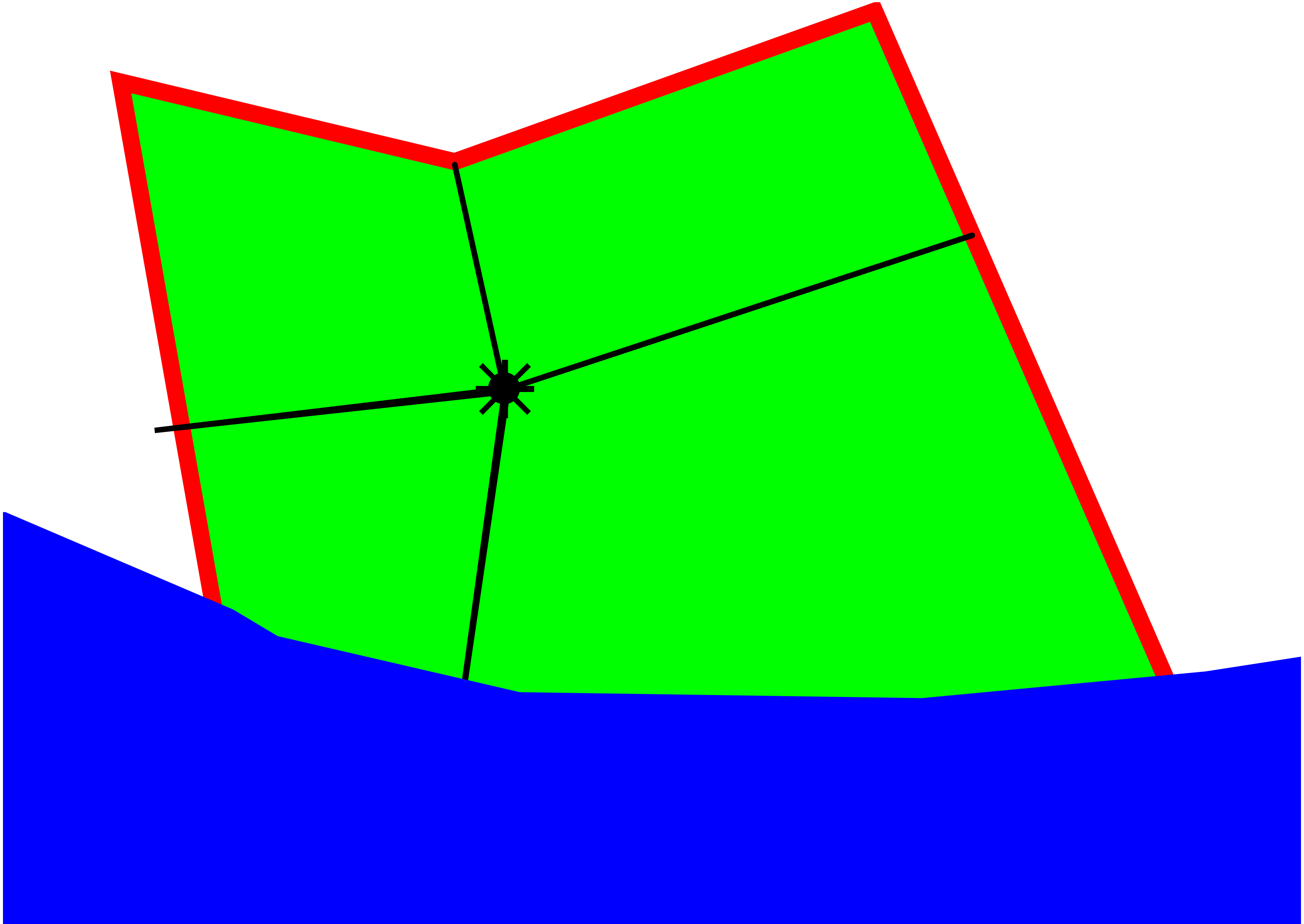
Monitoring the Water Contact

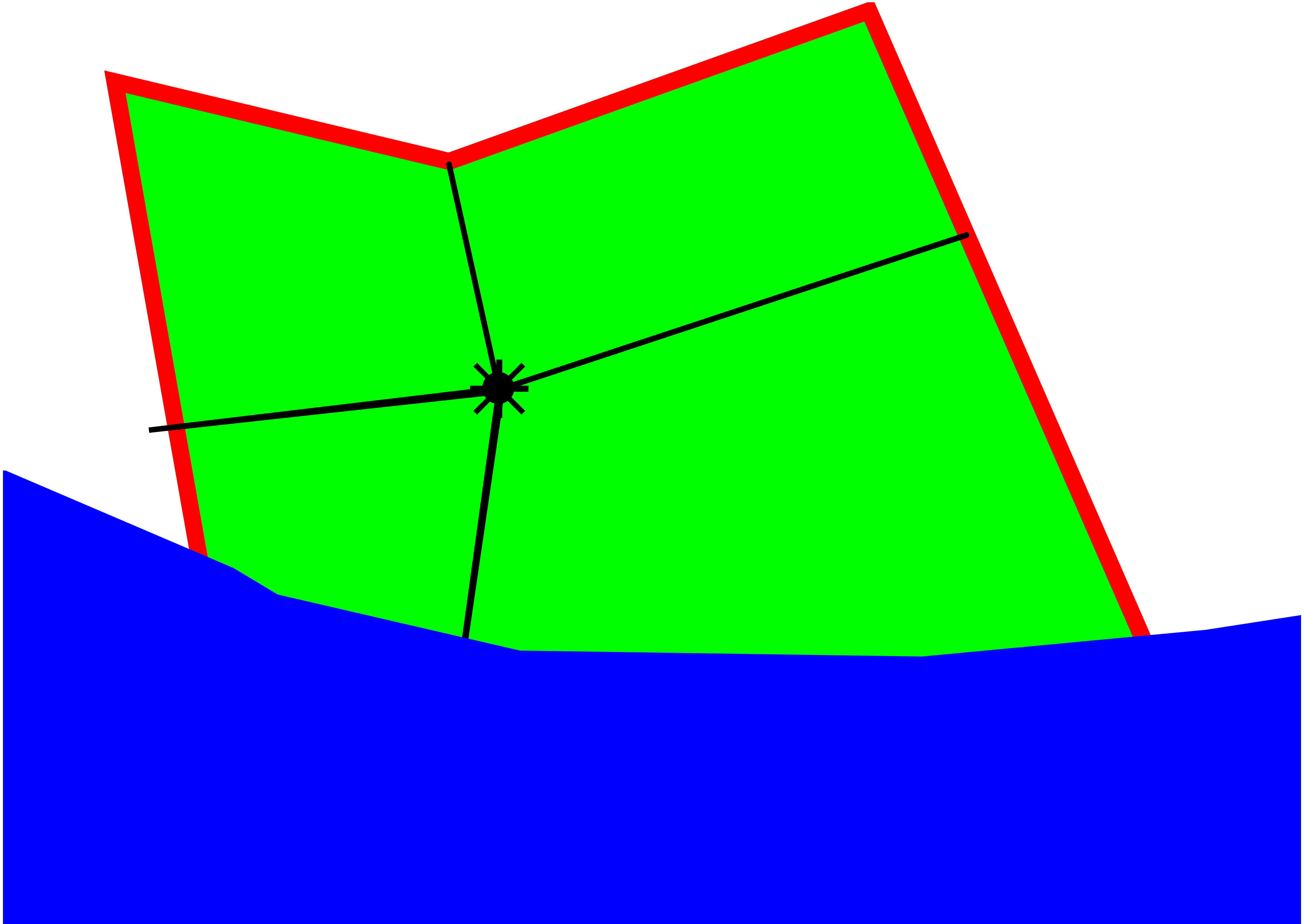
- **Initial Map of Limit Distances on Initial Drawdown.**
- **Next Shutin and Reopening of Well:**
  - **Retest**
  - **Identify Limit Distances**
  - **Compare Original With New Limit Distances**
- ***"The Limit That Moved"* is the Water.**

Original Configuration

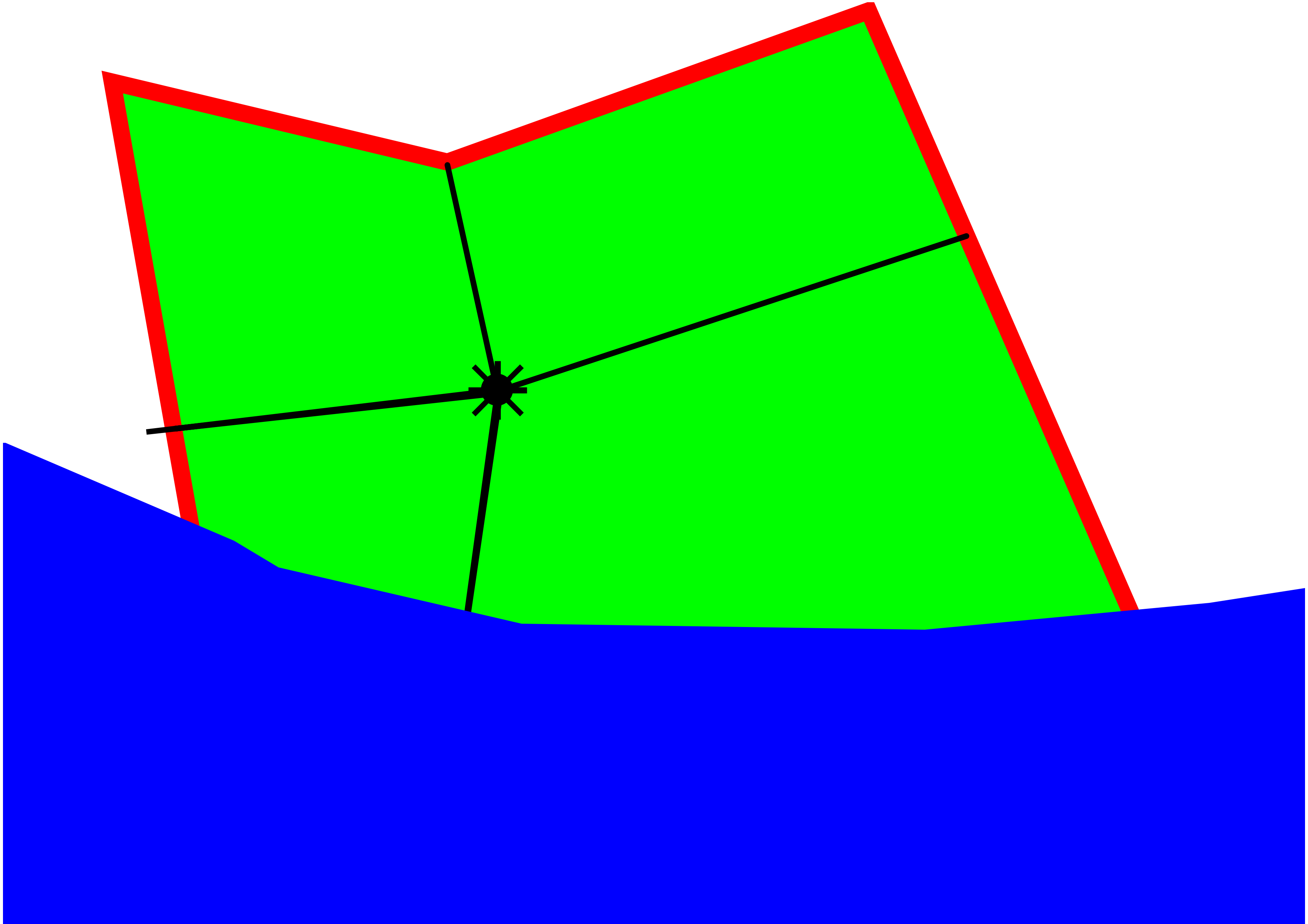


Water Begins to Move

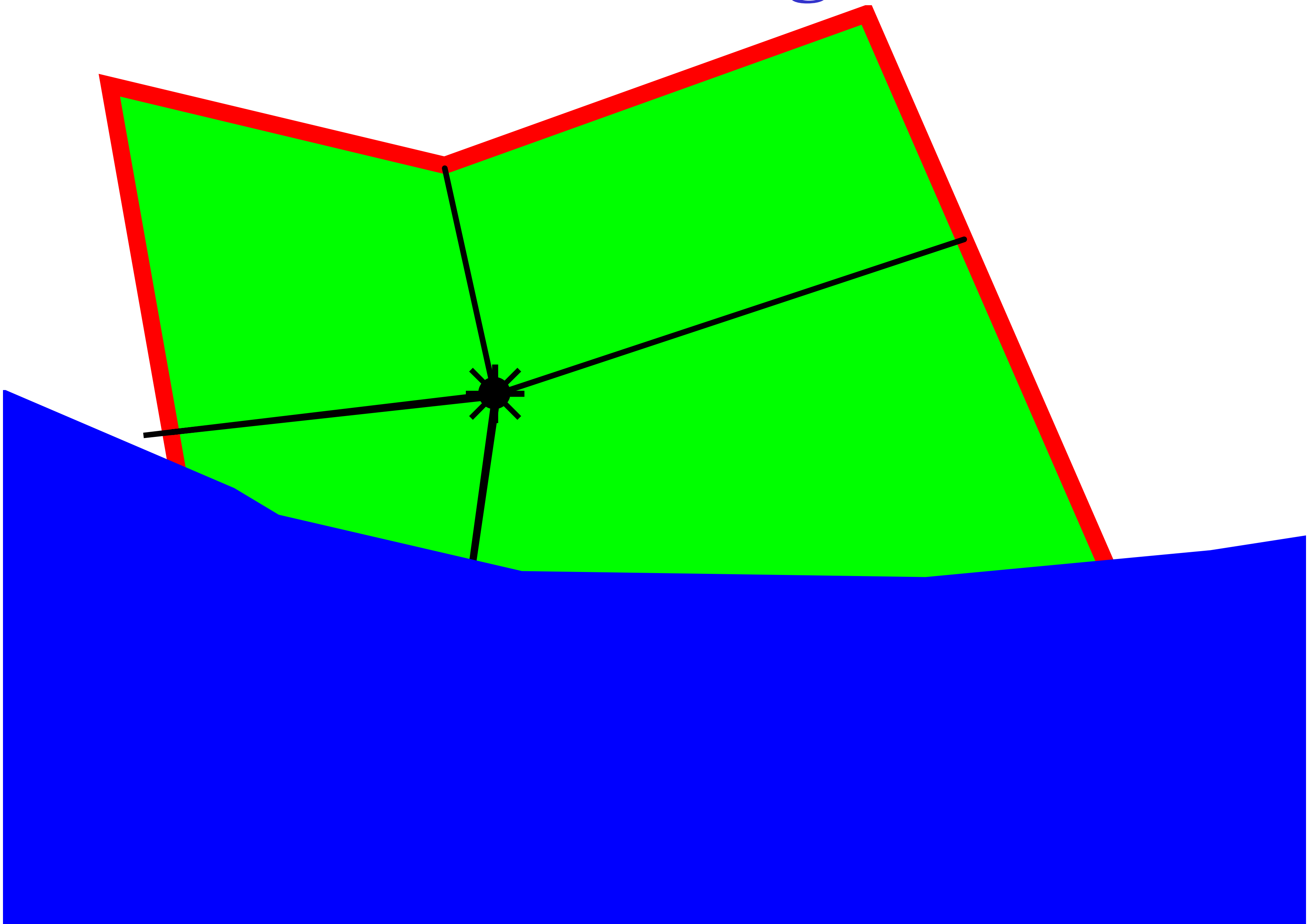




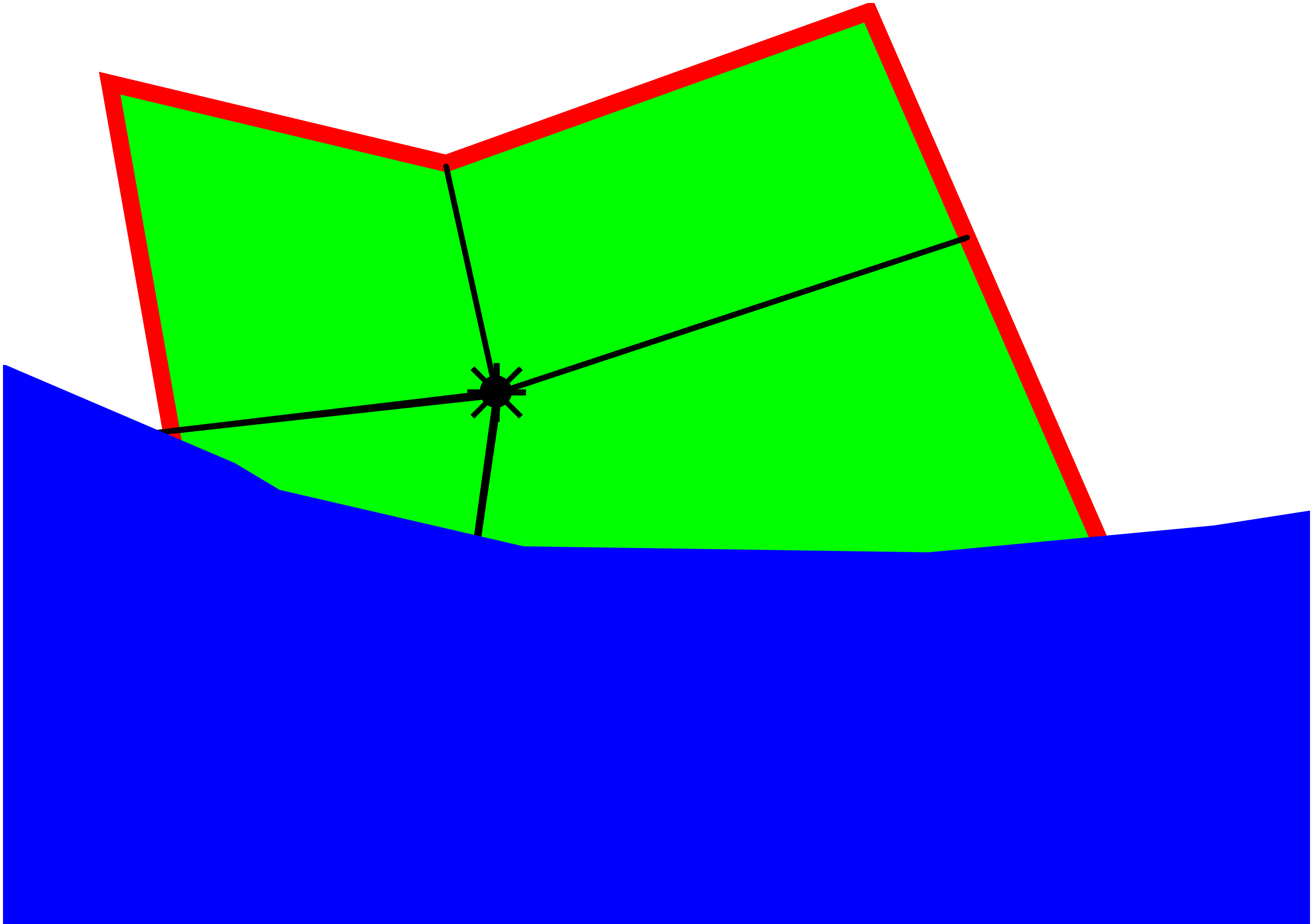
Water Boundary Movement Evident



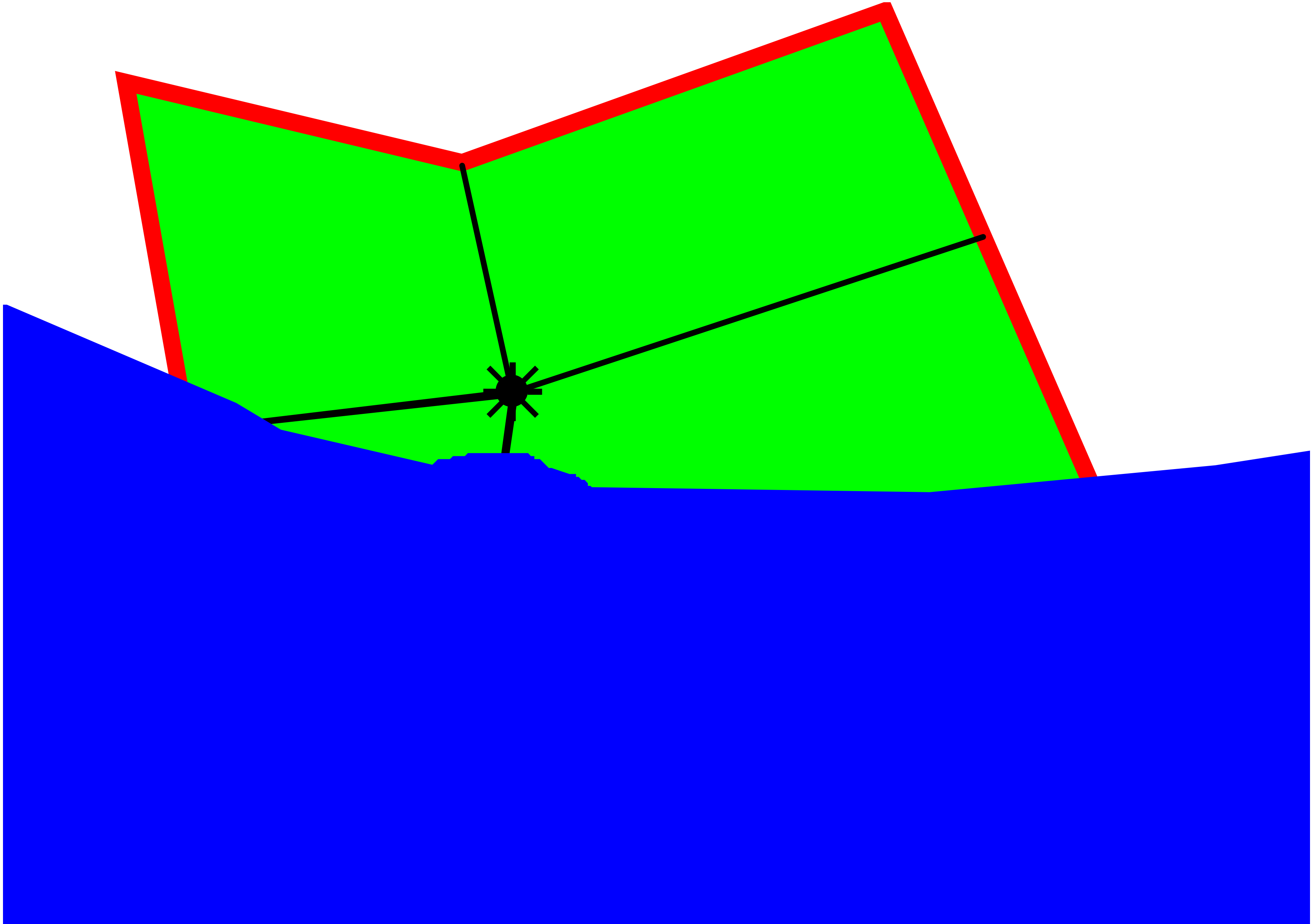
Monitoring!



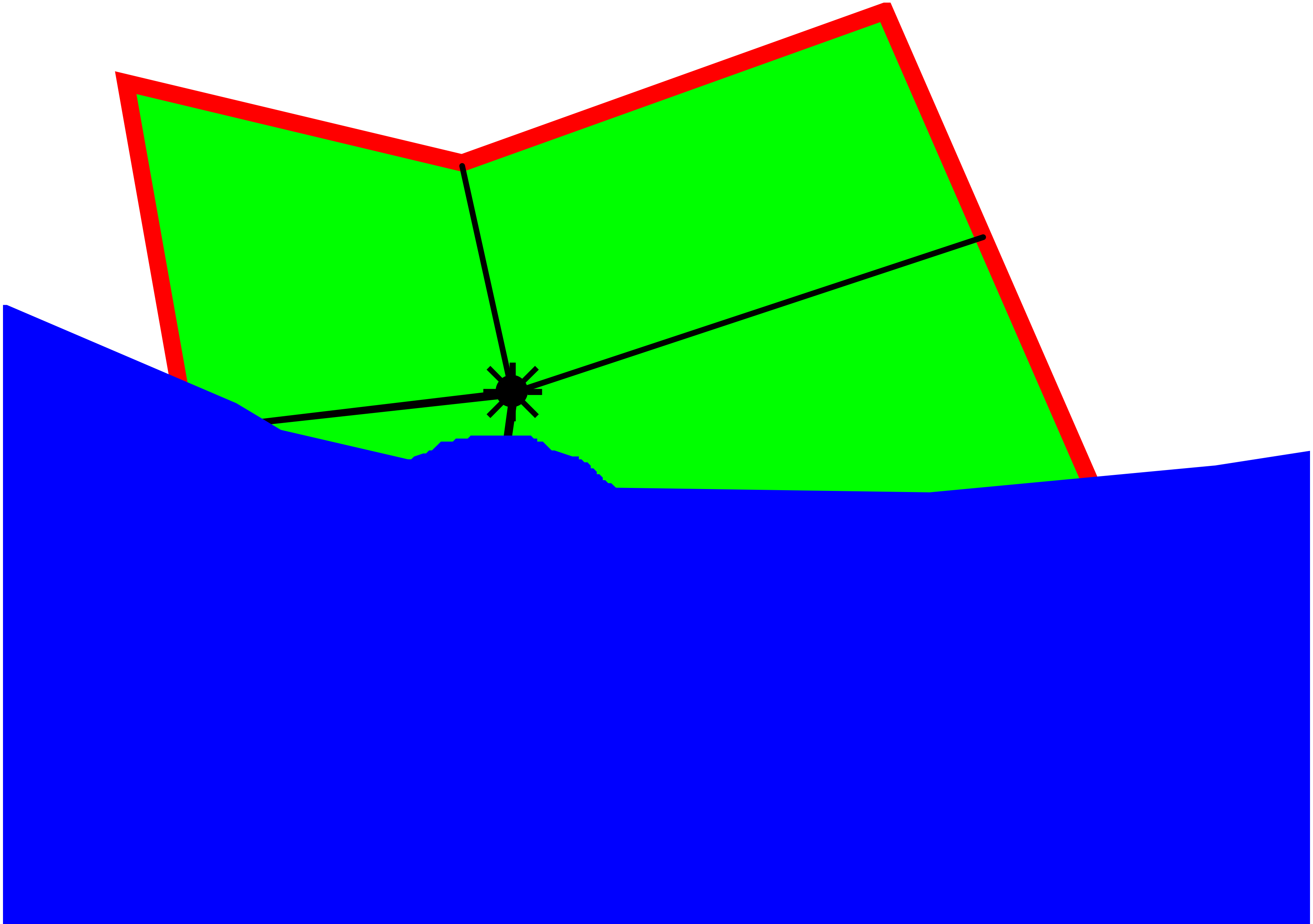
Water Too Close…Begin Rate Alert



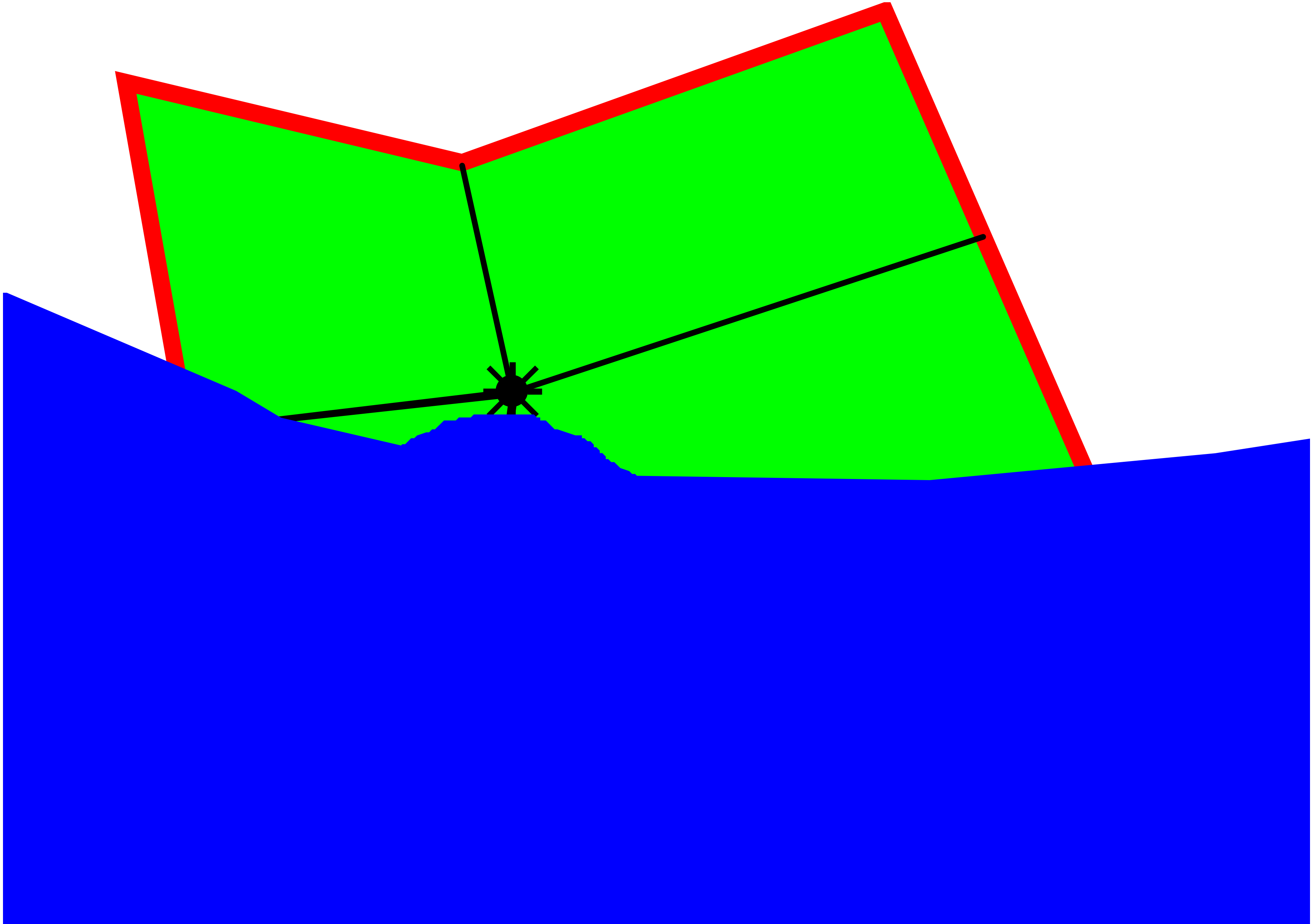
Water Finger Begins to Form



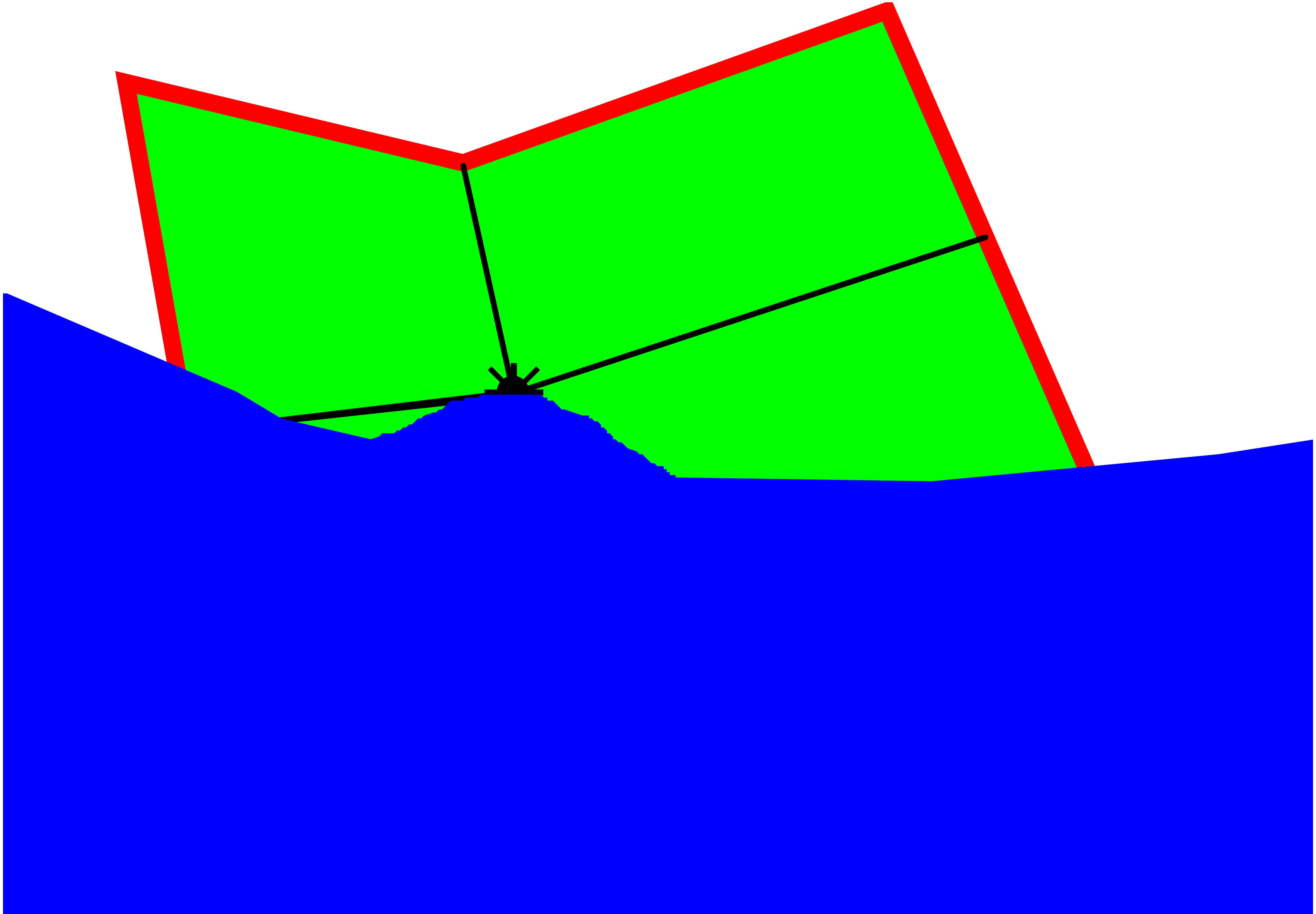
Cut Rate



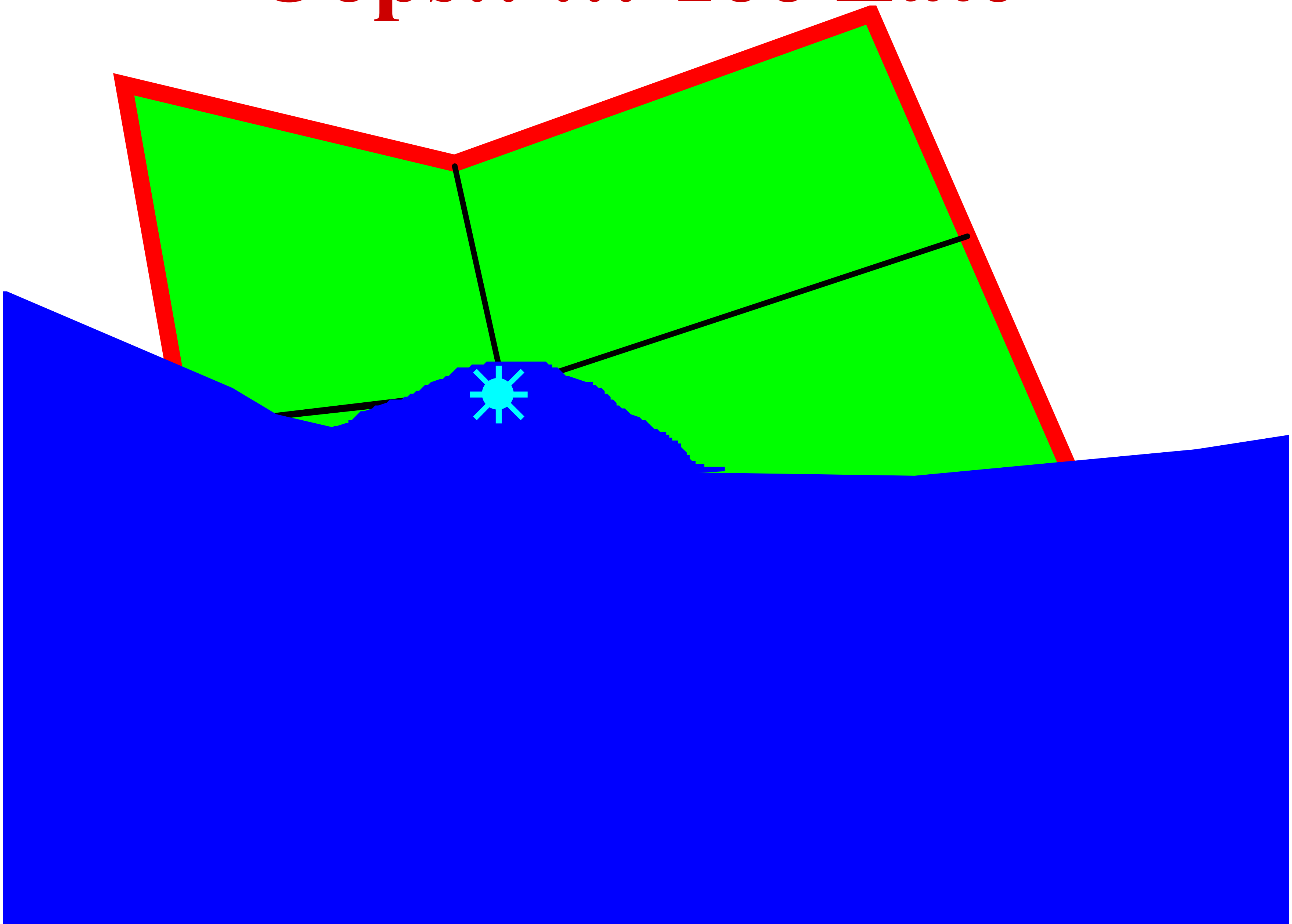
Cut Rate Again…Shut In Temporarily



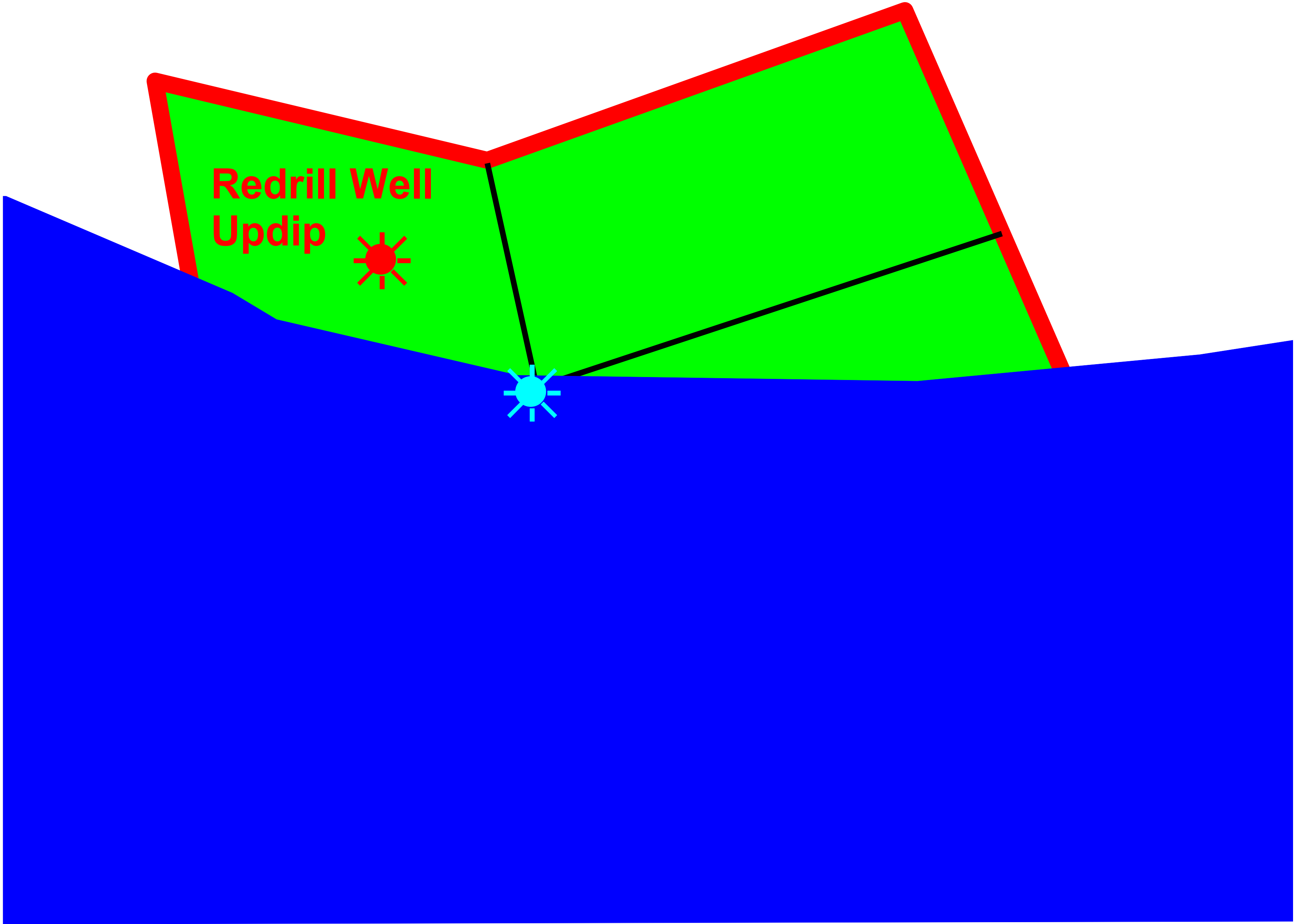
Shut In Now!



Oops!! … Too Late



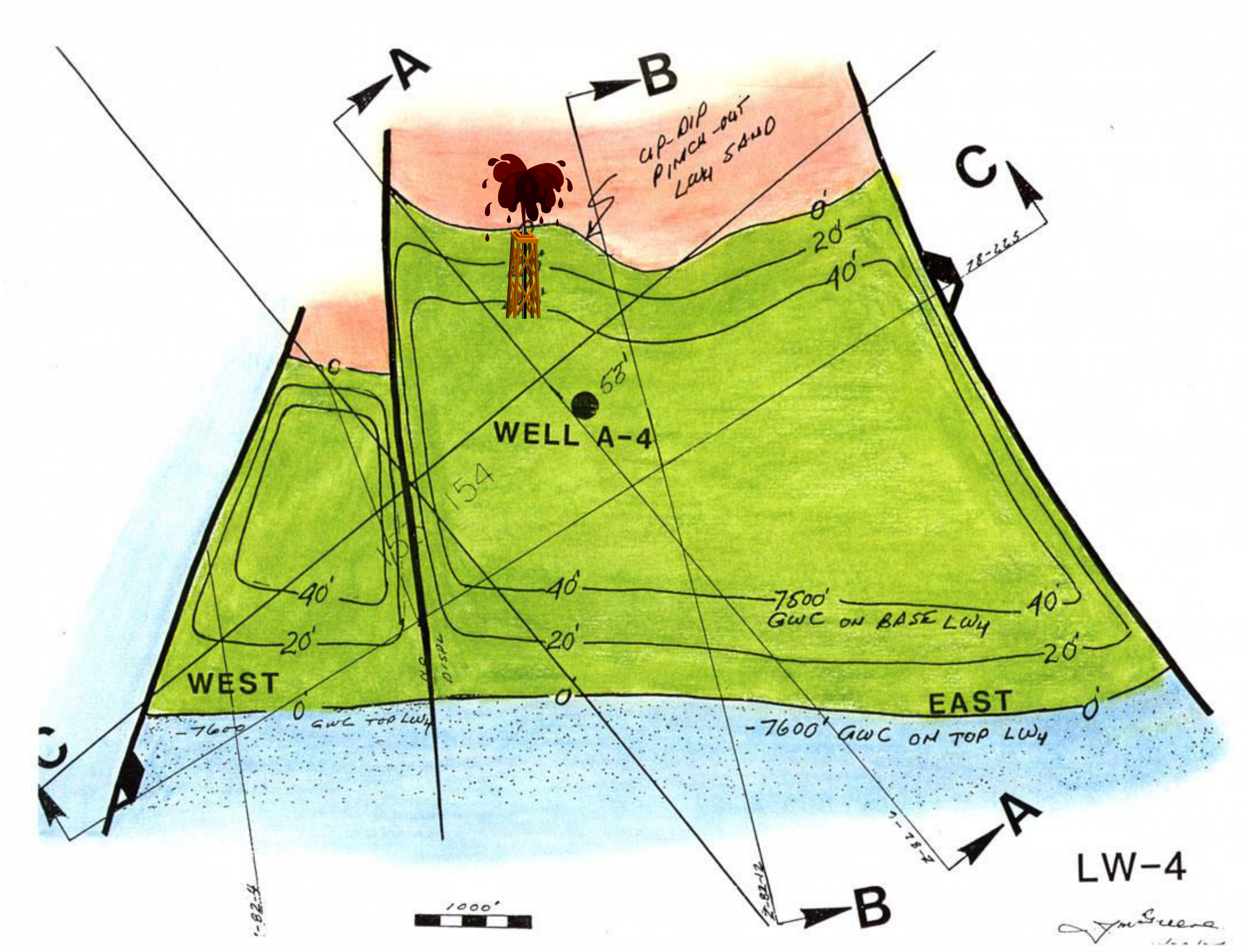
Stable Shutin Reservoir PUD



Reservoir History

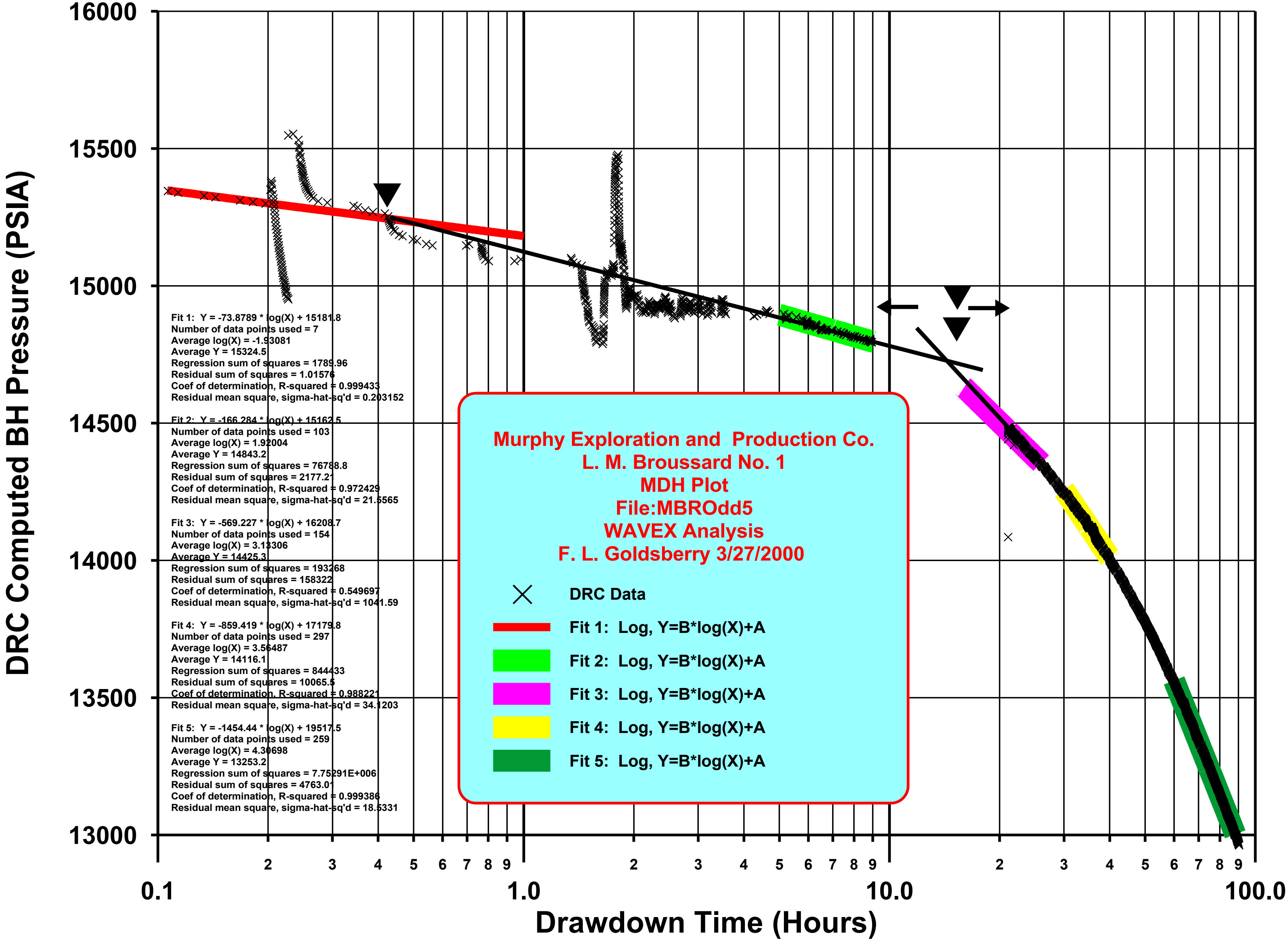
- **Map Volume 1987:**
  - **20 BCF PDP to Water Out**
  - **35 BCR Gas In Place**
- **Total Produced by 1993: 19.2 BCF** Until Original Well Watered Out.
- **Well Successfully Redrilled Up Dip 1994**.
- **Original Estimate Accuracy: 96%**

Drilling Results Updip

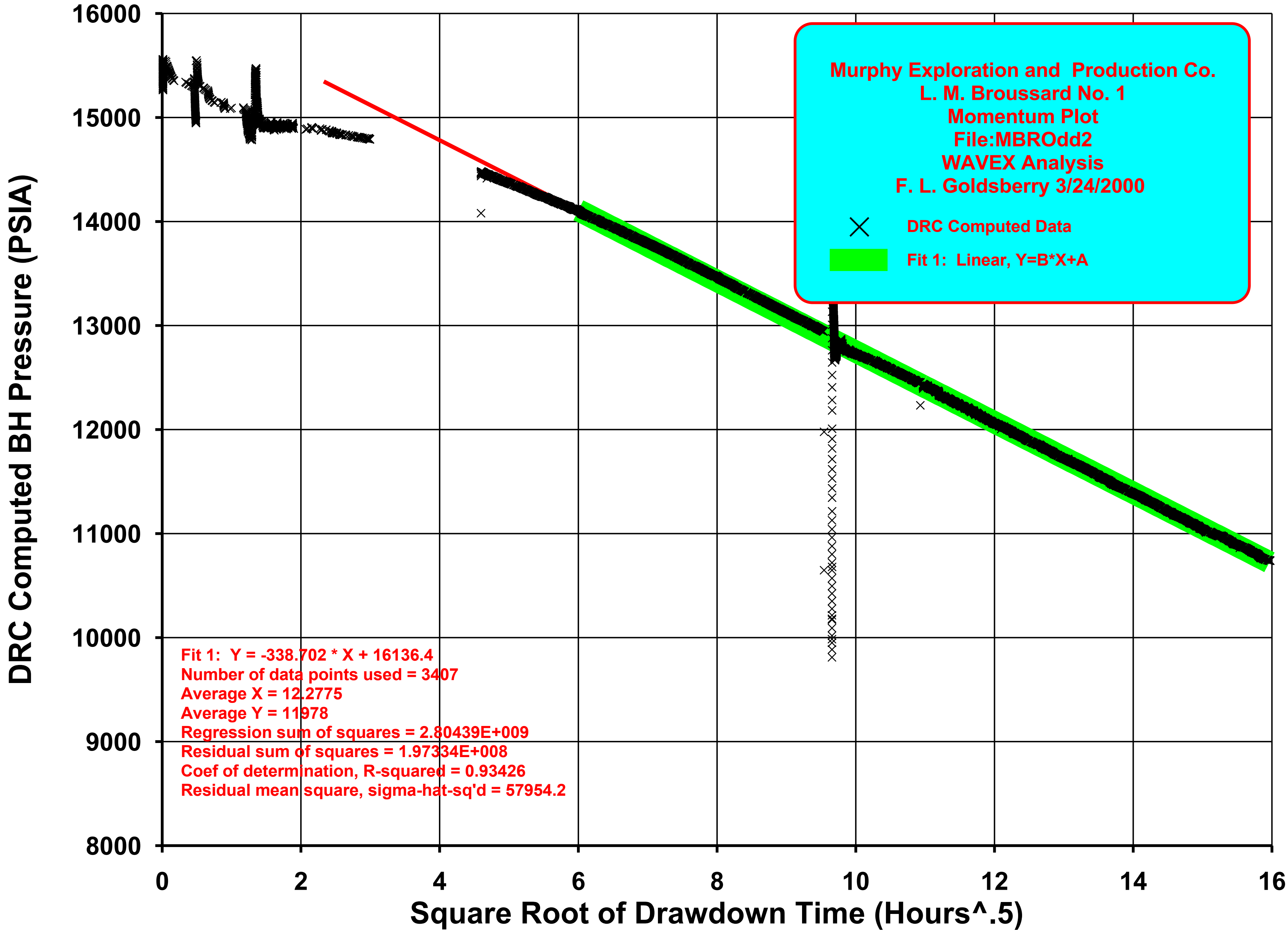


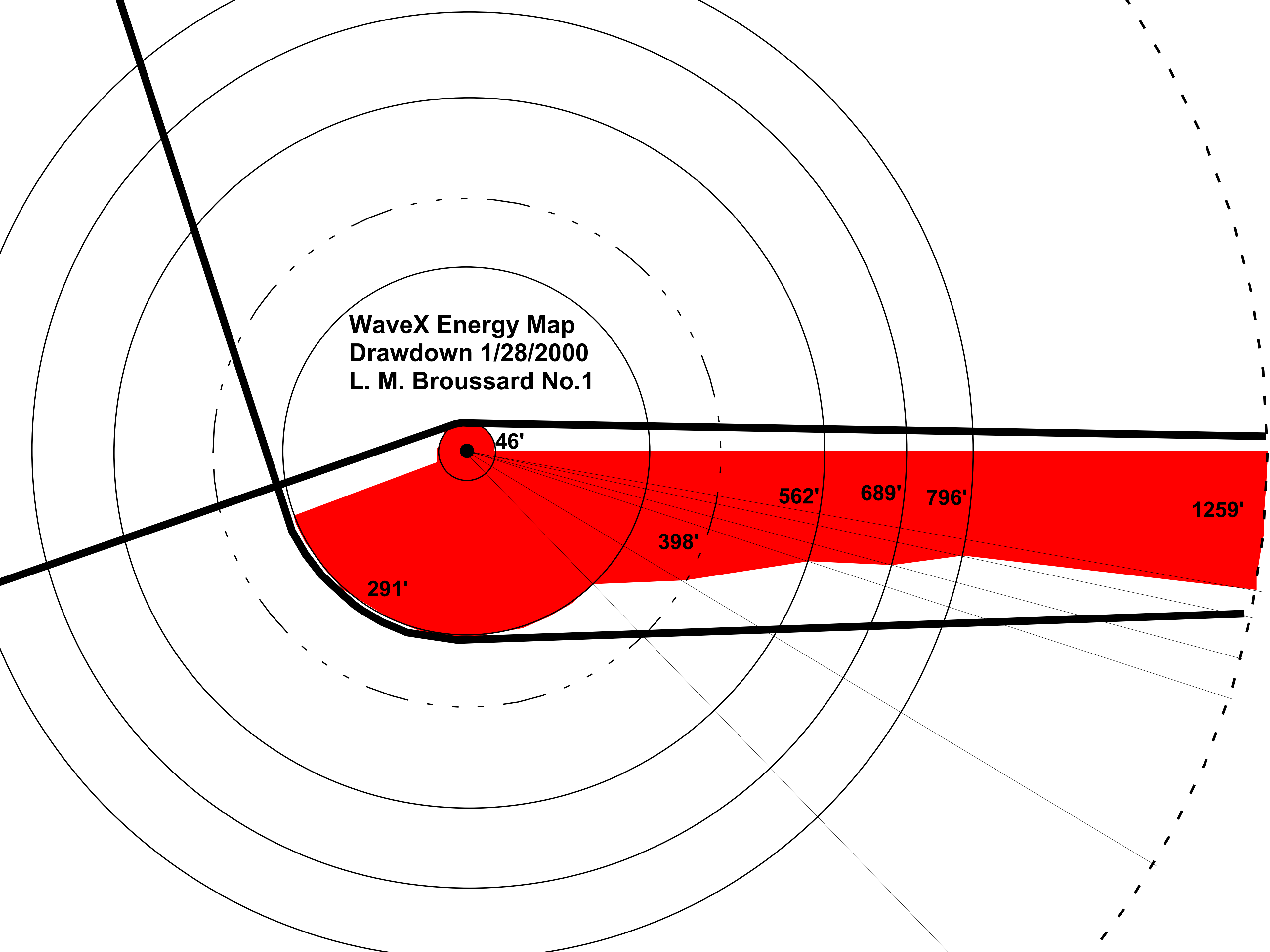
Water Approach Example

- Routine Monitoring of Depleting Well
- Rapidly Changing Fluid Properties
- Only One Geometric Parameter Changes........It Must Be a Moving Liquid Phase!

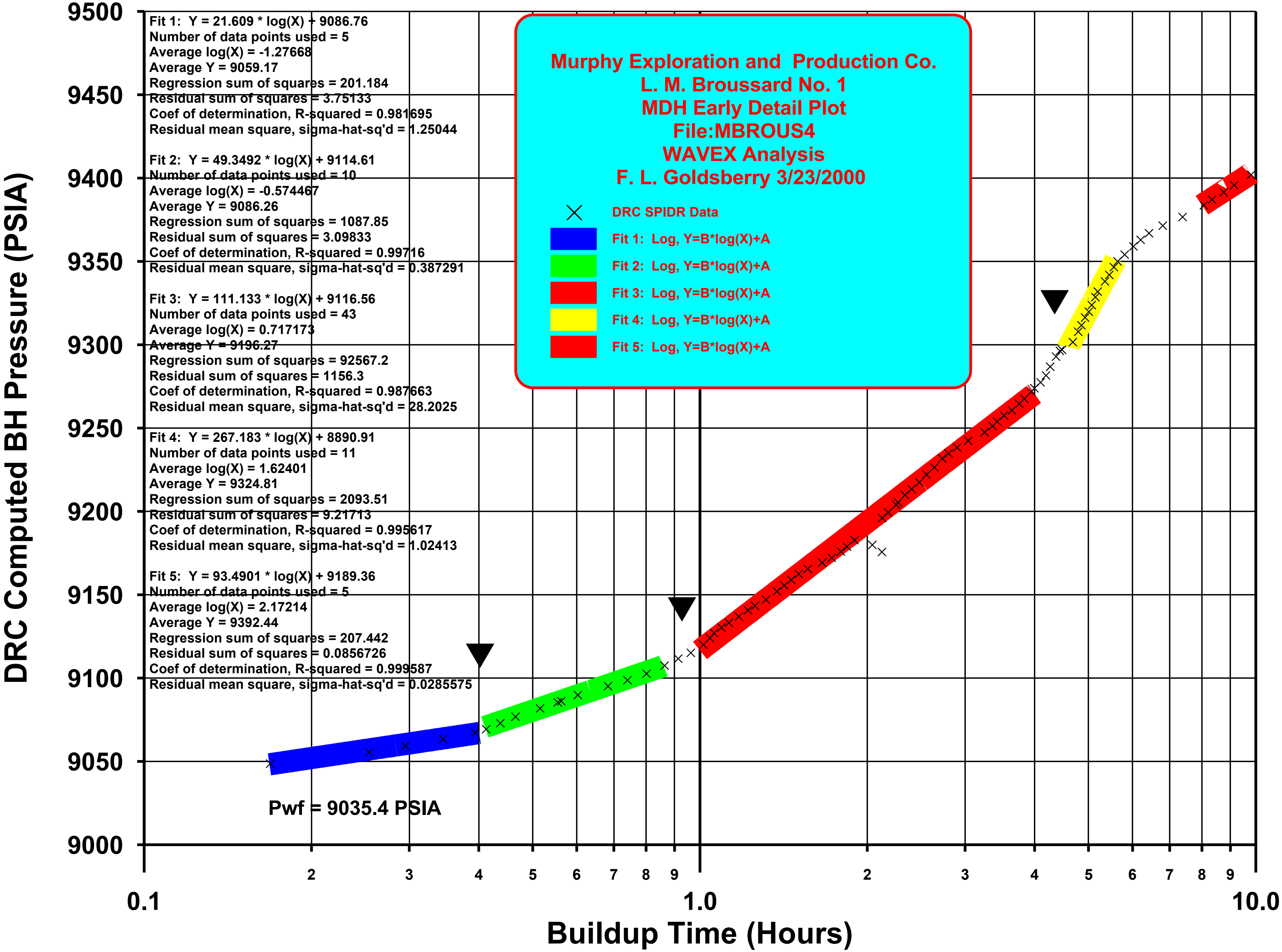


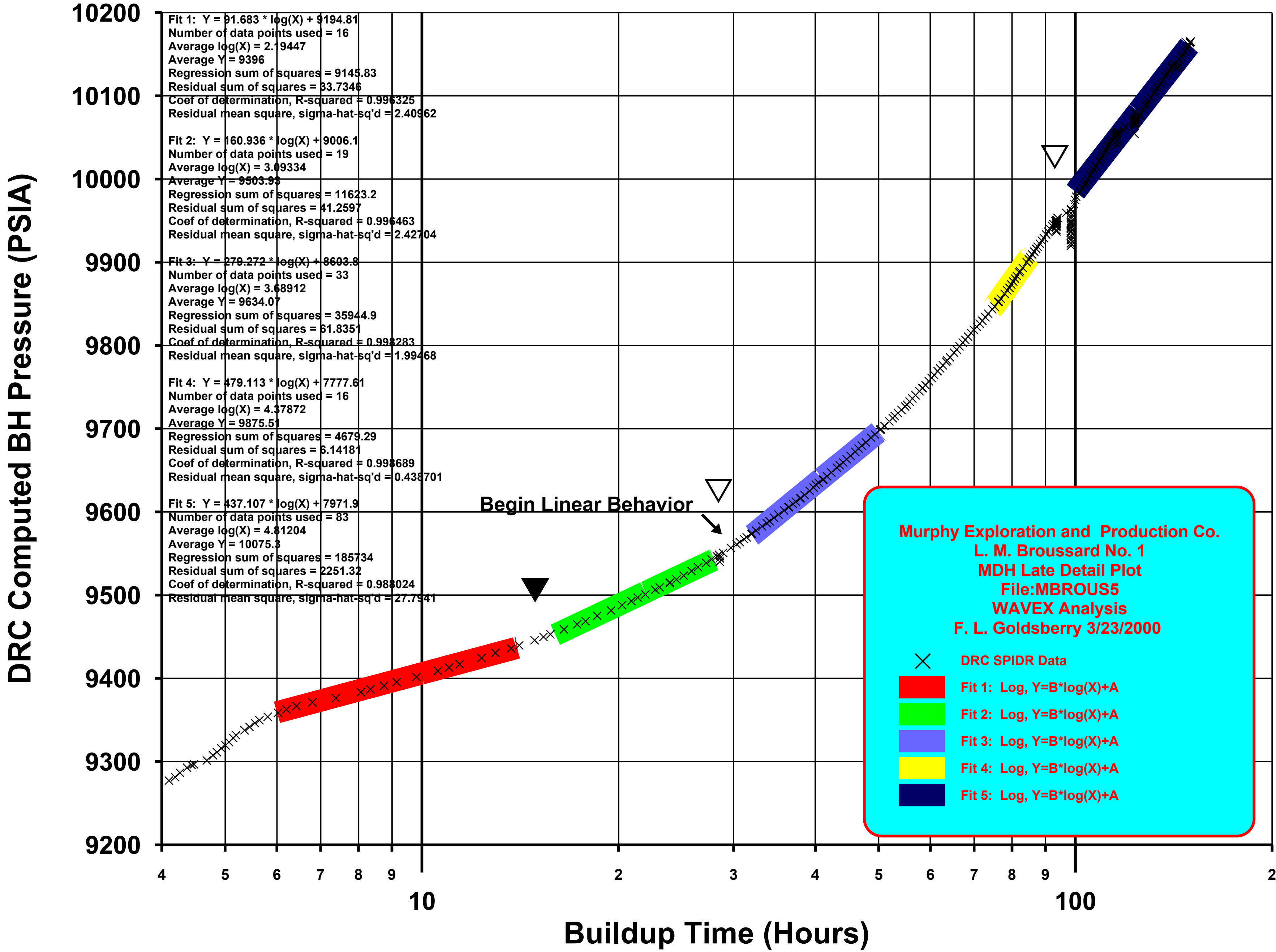
DRC Computed BH Pressure (PSIA)
16000
15500
15000
14500
14000
13500
13000
0.1
1.0
10.0
100.0
Drawdown Time (Hours)
Fit 1: Y = -73.8789 * log(X) + 15181.8
Number of data points used = 7
Average log(X) = -1.93081
Average Y = 15324.5
Regression sum of squares = 1789.96
Residual sum of squares = 1.01576
Coef of determination, R-squared = 0.999433
Residual mean square, sigma-hat-sq'd = 0.203152
Fit 2: Y = -166.284 * log(X) + 15162.5
Number of data points used = 103
Average log(X) = 1.92004
Average Y = 14843.2
Regression sum of squares = 76788.8
Residual sum of squares = 2177.21
Coef of determination, R-squared = 0.972429
Residual mean square, sigma-hat-sq'd = 21.5565
Fit 3: Y = -569.227 * log(X) + 16208.7
Number of data points used = 154
Average log(X) = 3.13306
Average Y = 14425.3
Regression sum of squares = 193268
Residual sum of squares = 158322
Coef of determination, R-squared = 0.549697
Residual mean square, sigma-hat-sq'd = 1041.59
Fit 4: Y = -859.419 * log(X) + 17179.8
Number of data points used = 297
Average log(X) = 3.56487
Average Y = 14116.1
Regression sum of squares = 844433
Residual sum of squares = 10065.5
Coef of determination, R-squared = 0.988221
Residual mean square, sigma-hat-sq'd = 34.1203
Fit 5: Y = -1454.44 * log(X) + 19517.5
Number of data points used = 259
Average log(X) = 4.30698
Average Y = 13253.2
Regression sum of squares = 7.75291E+006
Residual sum of squares = 4763.01
Coef of determination, R-squared = 0.999386
Residual mean square, sigma-hat-sq'd = 18.5331
Murphy Exploration and Production Co.
L. M. Broussard No. 1
MDH Plot
File:MBROdd5
WAVEX Analysis
F. L. Goldsberry 3/27/2000
DRC Data
Fit 1: Log, Y=B*log(X)+A
Fit 2: Log, Y=B*log(X)+A
Fit 3: Log, Y=B*log(X)+A
Fit 4: Log, Y=B*log(X)+A
Fit 5: Log, Y=B*log(X)+A

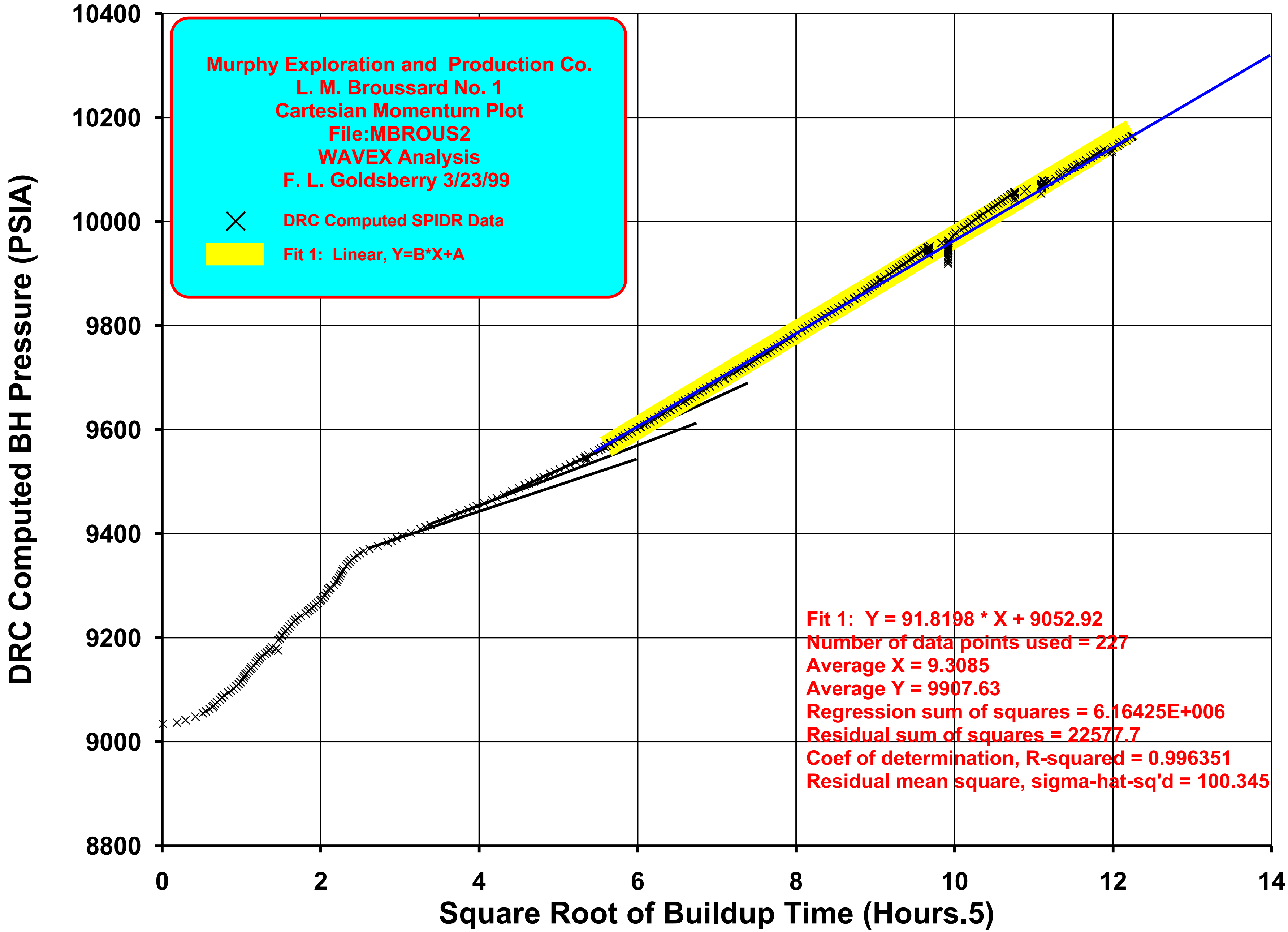

Murphy Exploration and Production Co.
L. M. Broussard No. 1
Momentum Plot
File:MBROdd2
WAVEX Analysis
F. L. Goldsberry 3/24/2000
DRC Computed Data
Fit 1: Linear, Y=B*X+A
Fit 1: Y = -338.702 * X + 16136.4
Number of data points used = 3407
Average X = 12.2775
Average Y = 11978
Regression sum of squares = 2.80439E+009
Residual sum of squares = 1.97334E+008
Coef of determination, R-squared = 0.93426
Residual mean square, sigma-hat-sq'd = 57954.2
DRC Computed BH Pressure (PSIA)
Square Root of Drawdown Time (Hours^.5)
16000
15000
14000
13000
12000
11000
10000
9000
8000
0
2
4
6
8
10
12
14
16

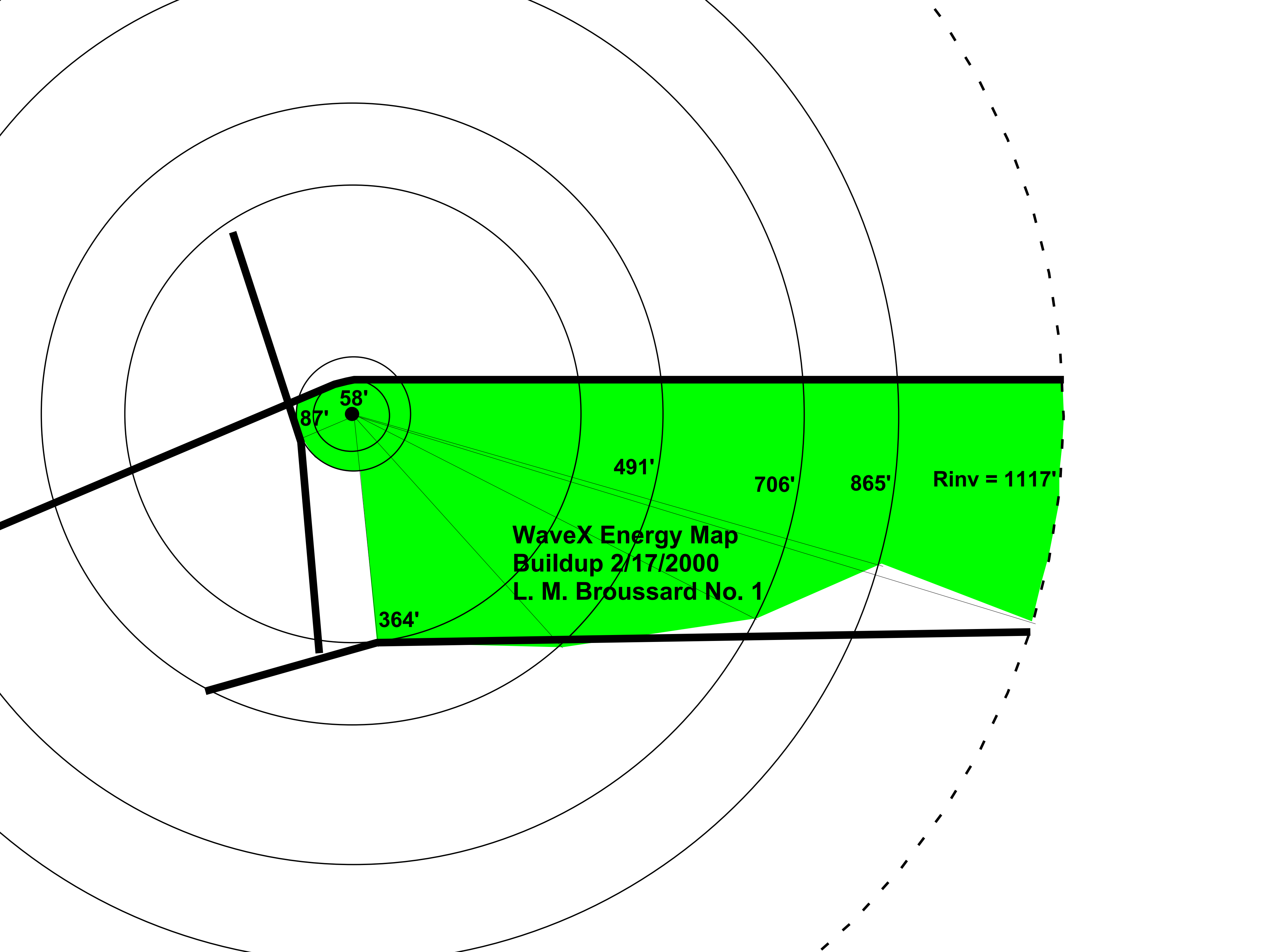


WaveX Energy Map
Drawdown 1/28/2000
L. M. Broussard No.1
46'
291'
398'
562'
689'
796'
1259'

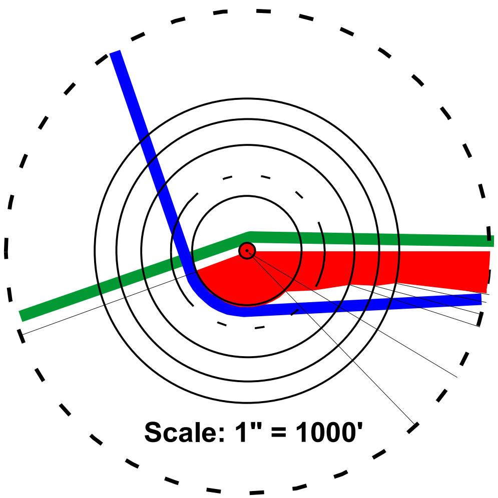

Fit 1: Y = 21.609 * log(X) + 9086.76
Number of data points used = 5
Average log(X) = -1.27668
Average Y = 9059.17
Regression sum of squares = 201.184
Residual sum of squares = 3.75133
Coef of determination, R-squared = 0.981695
Residual mean square, sigma-hat-sq'd = 1.25044
Fit 2: Y = 49.3492 * log(X) + 9114.61
Number of data points used = 10
Average log(X) = -0.574467
Average Y = 9086.26
Regression sum of squares = 1087.85
Residual sum of squares = 3.09833
Coef of determination, R-squared = 0.99716
Residual mean square, sigma-hat-sq'd = 0.387291
Fit 3: Y = 111.133 * log(X) + 9116.56
Number of data points used = 43
Average log(X) = 0.717173
Average Y = 9196.27
Regression sum of squares = 92567.2
Residual sum of squares = 1156.3
Coef of determination, R-squared = 0.987663
Residual mean square, sigma-hat-sq'd = 28.2025
Fit 4: Y = 267.183 * log(X) + 8890.91
Number of data points used = 11
Average log(X) = 1.62401
Average Y = 9324.81
Regression sum of squares = 2093.51
Residual sum of squares = 9.21713
Coef of determination, R-squared = 0.995617
Residual mean square, sigma-hat-sq'd = 1.02413
Fit 5: Y = 93.4901 * log(X) + 9189.36
Number of data points used = 5
Average log(X) = 2.17214
Average Y = 9392.44
Regression sum of squares = 207.442
Residual sum of squares = 0.0856726
Coef of determination, R-squared = 0.999587
Residual mean square, sigma-hat-sq'd = 0.0285575
Murphy Exploration and Production Co.
L. M. Broussard No. 1
MDH Early Detail Plot
File:MBROUS4
WAVEX Analysis
F. L. Goldsberry 3/23/2000
DRC SPIDR Data
Fit 1: Log, Y=B*log(X)+A
Fit 2: Log, Y=B*log(X)+A
Fit 3: Log, Y=B*log(X)+A
Fit 4: Log, Y=B*log(X)+A
Fit 5: Log, Y=B*log(X)+A
Pwf = 9035.4 PSIA
DRC Computed BH Pressure (PSIA)
9500
9450
9400
9350
9300
9250
9200
9150
9100
9050
9000
Buildup Time (Hours)
0.1
1.0
10.0
2
3
4
5
6
7
8
9


Fit 1: Y = 91.683 * log(X) + 9194.81
Number of data points used = 16
Average log(X) = 2.19447
Average Y = 9396
Regression sum of squares = 9145.83
Residual sum of squares = 33.7346
Coef of determination, R-squared = 0.996325
Residual mean square, sigma-hat-sq'd = 2.40962
Fit 2: Y = 160.936 * log(X) + 9006.1
Number of data points used = 19
Average log(X) = 3.09334
Average Y = 9503.93
Regression sum of squares = 11623.2
Residual sum of squares = 41.2597
Coef of determination, R-squared = 0.996463
Residual mean square, sigma-hat-sq'd = 2.42704
Fit 3: Y = 279.272 * log(X) + 8603.8
Number of data points used = 33
Average log(X) = 3.68912
Average Y = 9634.07
Regression sum of squares = 35944.9
Residual sum of squares = 61.8351
Coef of determination, R-squared = 0.998283
Residual mean square, sigma-hat-sq'd = 1.99468
Fit 4: Y = 479.113 * log(X) + 7777.61
Number of data points used = 16
Average log(X) = 4.37872
Average Y = 9875.51
Regression sum of squares = 4679.29
Residual sum of squares = 6.14181
Coef of determination, R-squared = 0.998689
Residual mean square, sigma-hat-sq'd = 0.438701
Fit 5: Y = 437.107 * log(X) + 7971.9
Number of data points used = 83
Average log(X) = 4.81204
Average Y = 10075.3
Regression sum of squares = 185734
Residual sum of squares = 2251.32
Coef of determination, R-squared = 0.988024
Residual mean square, sigma-hat-sq'd = 27.7941
Begin Linear Behavior
Murphy Exploration and Production Co.
L. M. Broussard No. 1
MDH Late Detail Plot
File:MBROUS5
WAVEX Analysis
F. L. Goldsberry 3/23/2000
DRC SPIDR Data
Fit 1: Log, Y=B*log(X)+A
Fit 2: Log, Y=B*log(X)+A
Fit 3: Log, Y=B*log(X)+A
Fit 4: Log, Y=B*log(X)+A
Fit 5: Log, Y=B*log(X)+A
DRC Computed BH Pressure (PSIA)
10200
10100
10000
9900
9800
9700
9600
9500
9400
9300
9200
4
5
6
7
8
9
10
2
3
4
5
6
7
8
9
100
2
Buildup Time (Hours)


Murphy Exploration and Production Co.
L. M. Broussard No. 1
Cartesian Momentum Plot
File:MBROUS2
WAVEX Analysis
F. L. Goldsberry 3/23/99
DRC Computed SPIDR Data
Fit 1: Linear, Y=B*X+A
Fit 1: Y = 91.8198 * X + 9052.92
Number of data points used = 227
Average X = 9.3085
Average Y = 9907.63
Regression sum of squares = 6.16425E+006
Residual sum of squares = 22577.7
Coef of determination, R-squared = 0.996351
Residual mean square, sigma-hat-sq'd = 100.345
DRC Computed BH Pressure (PSIA)
Square Root of Buildup Time (Hours.5)
10400
10200
10000
9800
9600
9400
9200
9000
8800
0
2
4
6
8
10
12
14

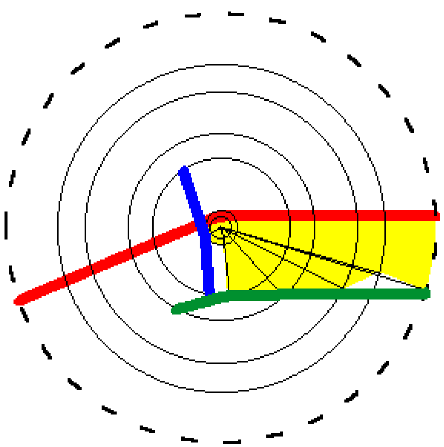

58'
87'
491'
706'
865'
Rinv = 1117'
364'
WaveX Energy Map
Buildup 2/17/2000
L. M. Broussard No. 1

Drawdown Energy Map w/ Limits Rotated



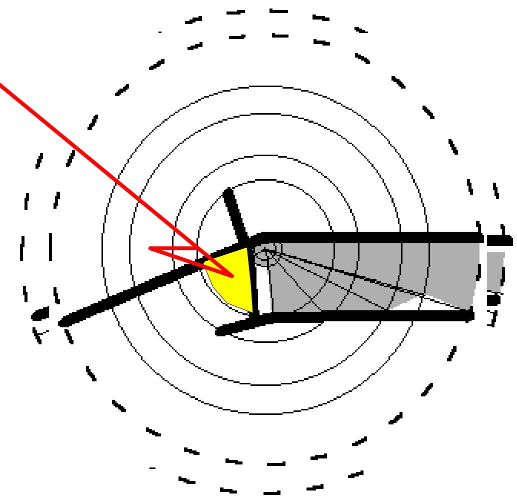
January 28, 2000

Buildup Energy Map w/ Limits Rotated



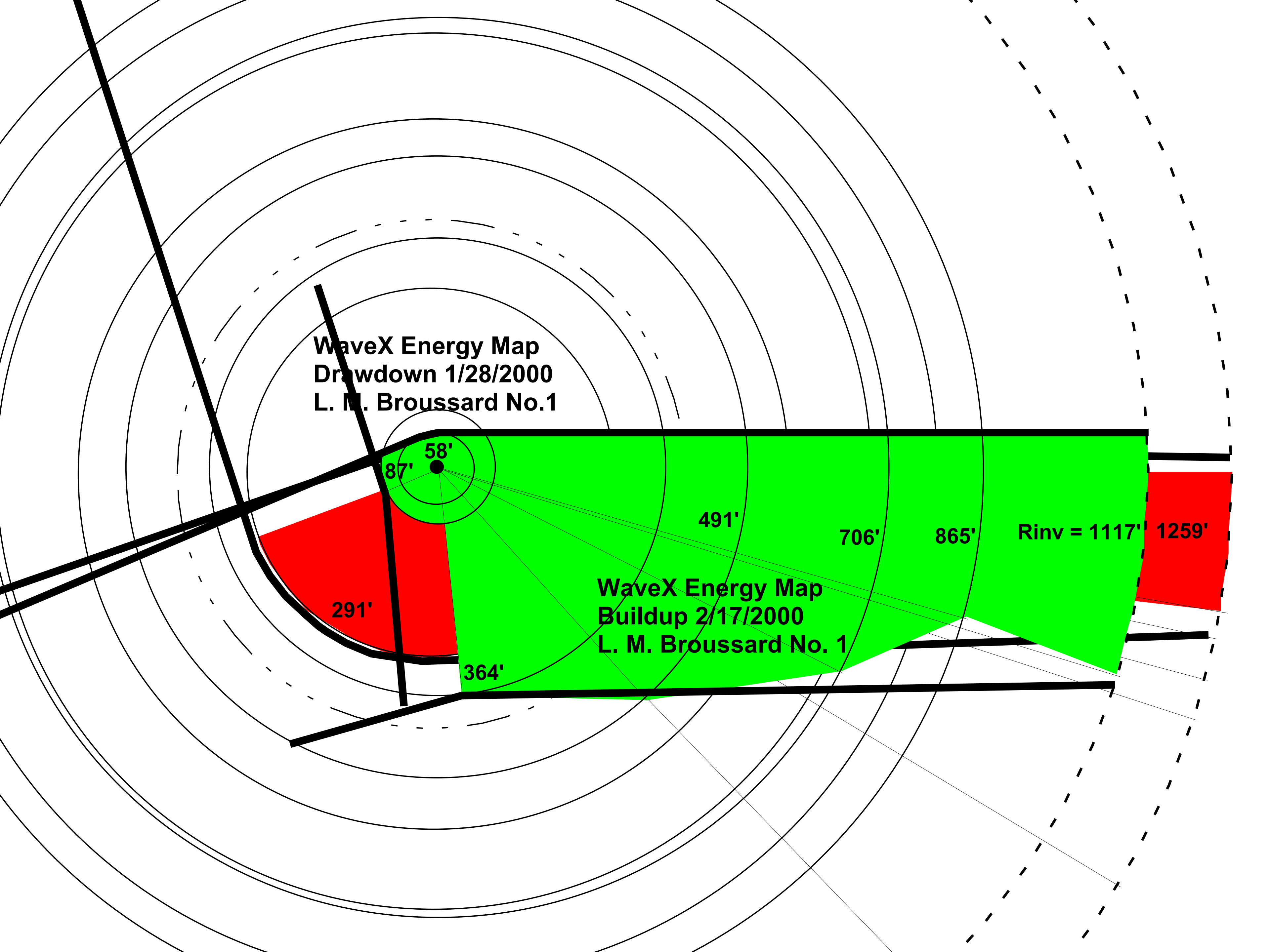
February 17, 2000

Overlay of Energy Maps
Note Area of Possible
Water Encroachment Between Tests

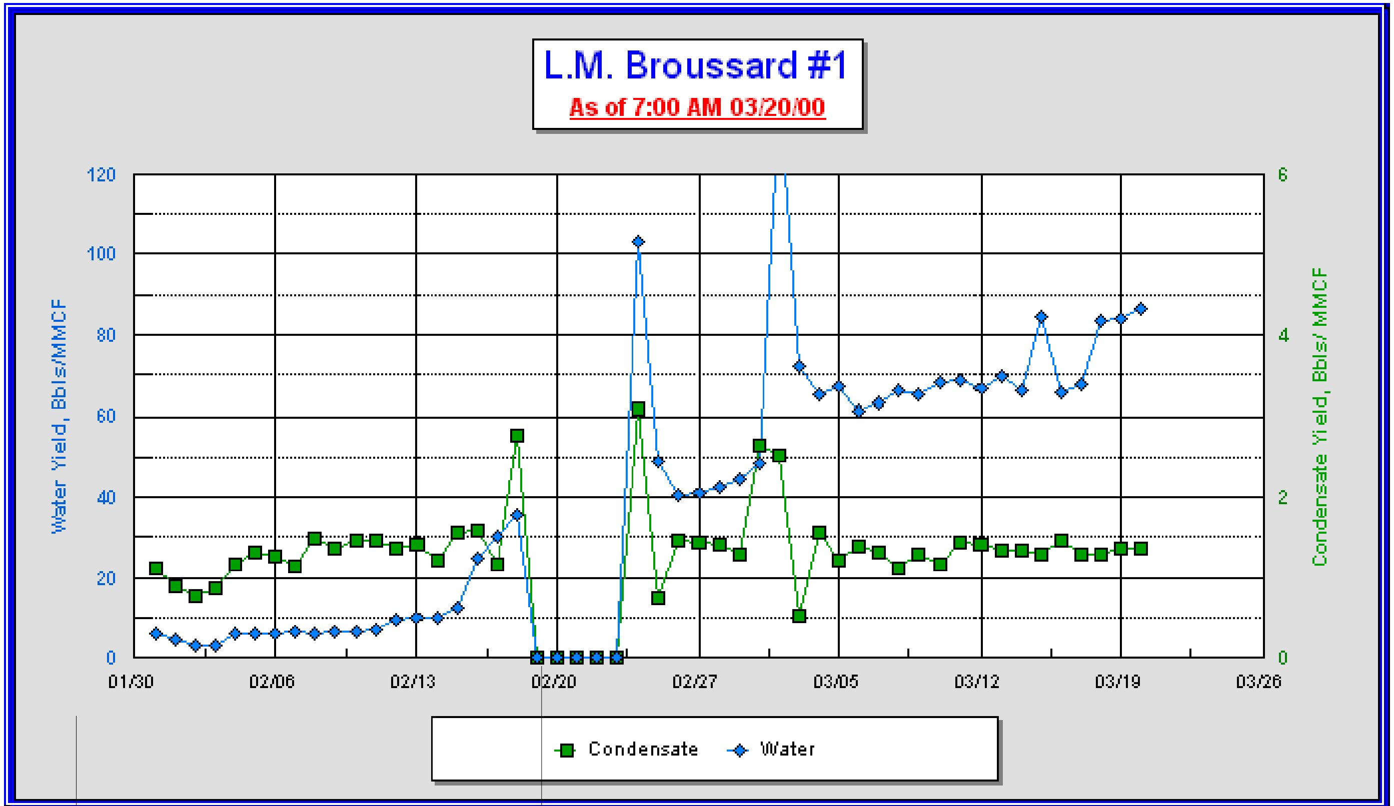


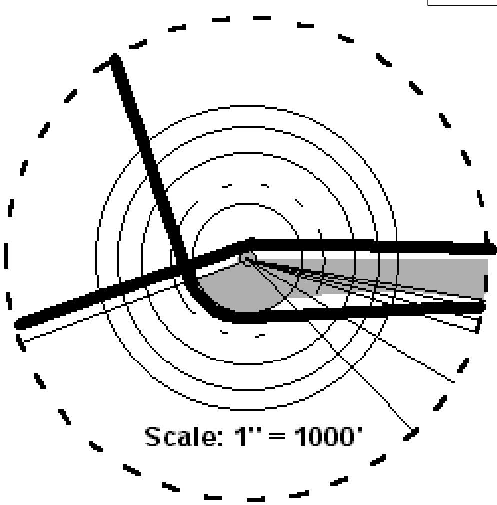
Area of Overlap is Approximately 1.8 Acres Containing .55 BCF.

Note: As the pressure decreases with time, so does hydraulic diffusivity. The diffusivity increases with distance from the well producing a distorted view of the reservoir. The noisy nature of the drawdown data increases the uncertainty of the picture of the drawdown. may be producing this apparent overlap in the energy maps. The well may water out in the near future. The time lapse energy maps from the pressure data indicate that a boundary is moving toward the well.

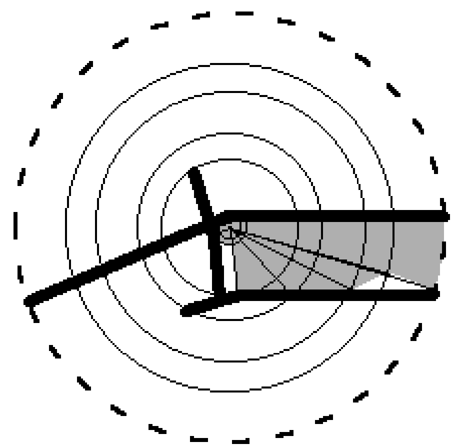


WaveX Energy Map
Drawdown 1/28/2000
L. M. Broussard No.1
58'
87'
291'
364'
491'
706'
865'
Rinv = 1117'
1259'
WaveX Energy Map
Buildup 2/17/2000
L. M. Broussard No. 1





January 28, 2000



February 17, 2000

Energy Shifts Can Be Detected

- Exploration and Recognition of the Initial Well/Reservoir Configuration Before Drilling
  - Geologic Mapping
  - 3D Seismic
- Confirmation and Monitoring after Drilling the Discovery Well
  - 4D Seismic
  - WaveX® Energy Dimensioning and Imaging

WaveX® Technology

- Funicular Stacking to Identify Limits
- BARLOG™ to Simplify and Normalize Relative Limit Movements
- Energy Integrals to Spot Accelerating Volume Changes
- Rate of Change Comparisons to Detect Fingering

More Information Recovery

- **Diffusion Model**
- **Estimated Distance to Limit 1** **"Get What You Guess" History Match Shape Usually the *Wrong Size.***
- **Distance to Limit = .749 $(nt)^{1/2}$**

- **WAVEX® Model**
- **Distance to Limit 1**
- **Shape of Limit 1**
- **Distance to Limit 2**
- **Shape of Limit 2**
- **Distance to Limit 3**
- **Shape of Limit 3**
- **Distance to Limit 4**
- **Shape of Limit 4**
- **Relative Dispositions of Limits 1 and 2**
- **Volume Explored Inplace as the Test Progresses.** ***The longer you test the more you map.***
- **Limit Map**
- **Drive Mechanism**
- **Distance to Limit = 2 $(nt)^{1/2}$**

WaveX®, Inc.

Reservoir Dimensioning

"Catch the WAVE"