The Impact of Perforating on Hydraulic Fracture Initiation in highly stress tough rock – a case study

射孔对于水力压裂在高应力致密岩石的起裂的影响——案例研究

China International Perforating Symposium
Oct 15-17

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OUTLINE 大纲

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ASSET OVERVIEW 概述

■Country: China 国家：中国

■Objective: To appraise BCG Play concept and assess productivity 目标：评价BCG（盆地中心气）理论，估算产能

■Appraising & Exploring using 9 vertical wells 9口直井用于评估&勘探

—Reservoir depth: 3500-4700 m 储层深度：3500-4700米

—Multiple targets of sand stone and carbonate formation目的层位于砂岩和碳酸岩地层

—**Tight formation**: 0.002-0.05 mD 紧岩层

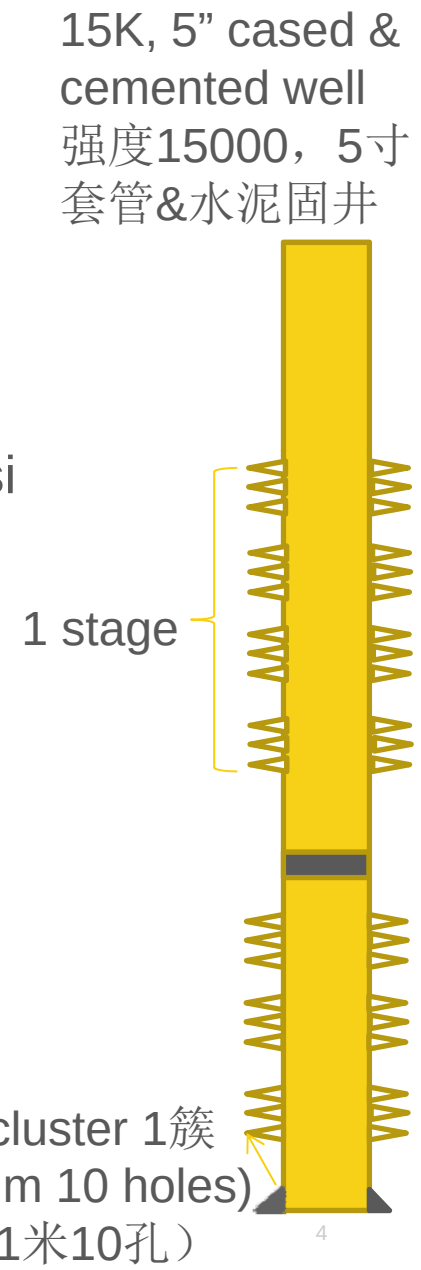
—**High pore pressure**: 17-23 kpa/m (0.75-1.01 psi/ft) 高孔隙压力

—**High stress**: Mixed reverse fault / Strike slip 高应力：多期逆断层/走滑

—**High rock strength** : YM 30-65 Gpa 高岩石强度：杨氏模量 30-65GPa

Completion Strategy 完井策略

- Fracturing using plug & perforation使用桥塞&射孔联作的压裂施工
  - 5 stages per well 每口井5层
  - Using heavy brine CaCl2 用重盐水氯化钙
  - Max. pump pressure 14,200 psi最大施工压力14200psi
  - Initially, using limited entry perforation of 3 or 4 x 1 m interval w/ 10-12 shots/m 起初，采用限流法射孔，每层3或4个长度1米的射孔簇，每米10到12孔
  - HCl and 100 mesh proppant 盐酸和100目粉砂
  - Hybrid slick water & gel frac 混合压裂（滑溜水&胶液）
  - Intermediate proppant strength 中强度支撑剂
- Pressure up 5-10 cycles for breakdown.
  - If fail to breakdown/ establish rate, add perforation



Perforation Strategy 完井策略

- Limited entry perforation of 3 or 4 cluster of 1 m with spacing 5-10 m
  限流法射孔，每个射孔簇1米，总共3或4个射孔簇，间距5-10米
  - To connect the clusters and create longer frac height 沟通不同的射孔簇，创造更大的裂缝高度
- Perforating gun, 2 7/8”, 18 g HMX, 60 deg phasing, 10-12 shot/m
  - 0.28” entrance diameter, 26” (660 mm)

射孔枪，外径2-7/8 “，18克HMX射孔弹，60度相位，10-12孔每米，孔眼大小0.28”，穿透深度660毫米

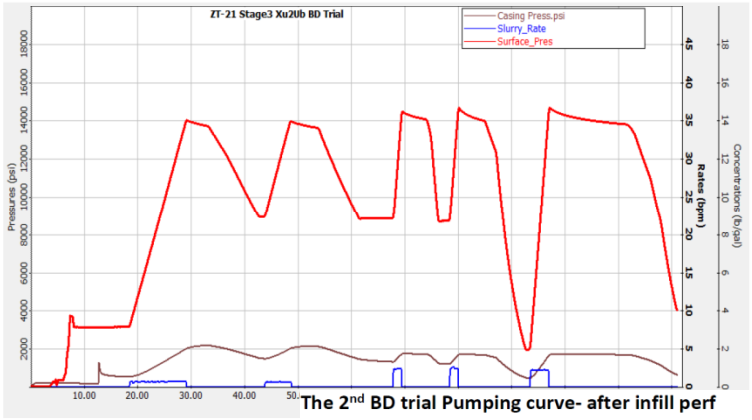
Test	EHD (mm)	Penetration (mm)
#1	7.3x7.1	691
#2	7.4x7.2	696
#3	7.6x7.3	671
Average	7.3	686

Challenges, Causes and Remediation 挑战，原因，补救

- Key challenges in first 3 wells (17 stages) 最初3口井的重大挑战（17层）
  - —Fail to break-down formation (4 stages) 不能破裂地层（4层）
  - —Not enough rate to continue w/ proppant fracturing (3 stages)不能建立排量或排量不足以加砂（3层）
  - —Only 1 dominant cluster and limited height只有1个主要的有效射孔簇，裂缝高度受限
- Potential Causes 潜在原因
  - —Tough, high rock stresses and high pressure 坚硬的岩石，高应力，高压
  - —Deep formation 深储层
  - —Near wellbore damage due to perforation/ drilling 钻井/射孔引起的近井筒污染
- Several remediation measures 补救措施
  - —Select less tougher rock (< 48 Gpa) 选择不那么坚硬的岩石（<48 GPa)
  - —Increase max. pump pressure 提高最大泵压
  - —Use heavier brine用更重的盐水
  - —Spot acid to remove near wellbore damage 注酸解除近井筒污染
  - —Open hole completion 裸眼完井
  - —Change perforating strategy (0 degree phasing, long perforation interval, sand jetting & Reactive charge) 改变射孔方案 (0度相位,长射孔段,喷砂射孔 & 活性弹)

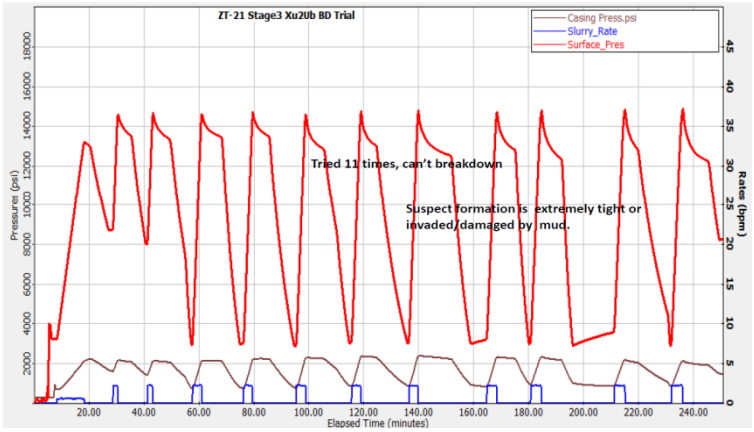
Example of pumping cycles in a stage at lower sandstone formation
某层下部的砂岩储层的泵注循环

The 1st BD trial Pumping curve- before infill perf



1. Reactive Charge, depth 4496-4499.6 m, 36 holes, 0.37 EHD, 60 degree phasing. Trialed 5 pumping cycle, no breakdown at pump limit 14,800 psi (1.58 psi/ft).活性弹，深度4496-4499.6 m，36孔，0.37”孔径，60度相位。泵注5次，在压力限制14800PSI下未能破裂地层

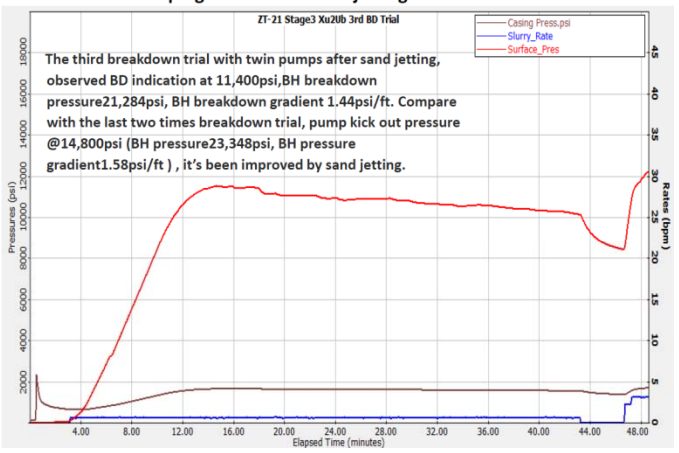
The 2nd BD trial Pumping curve- after infill perf



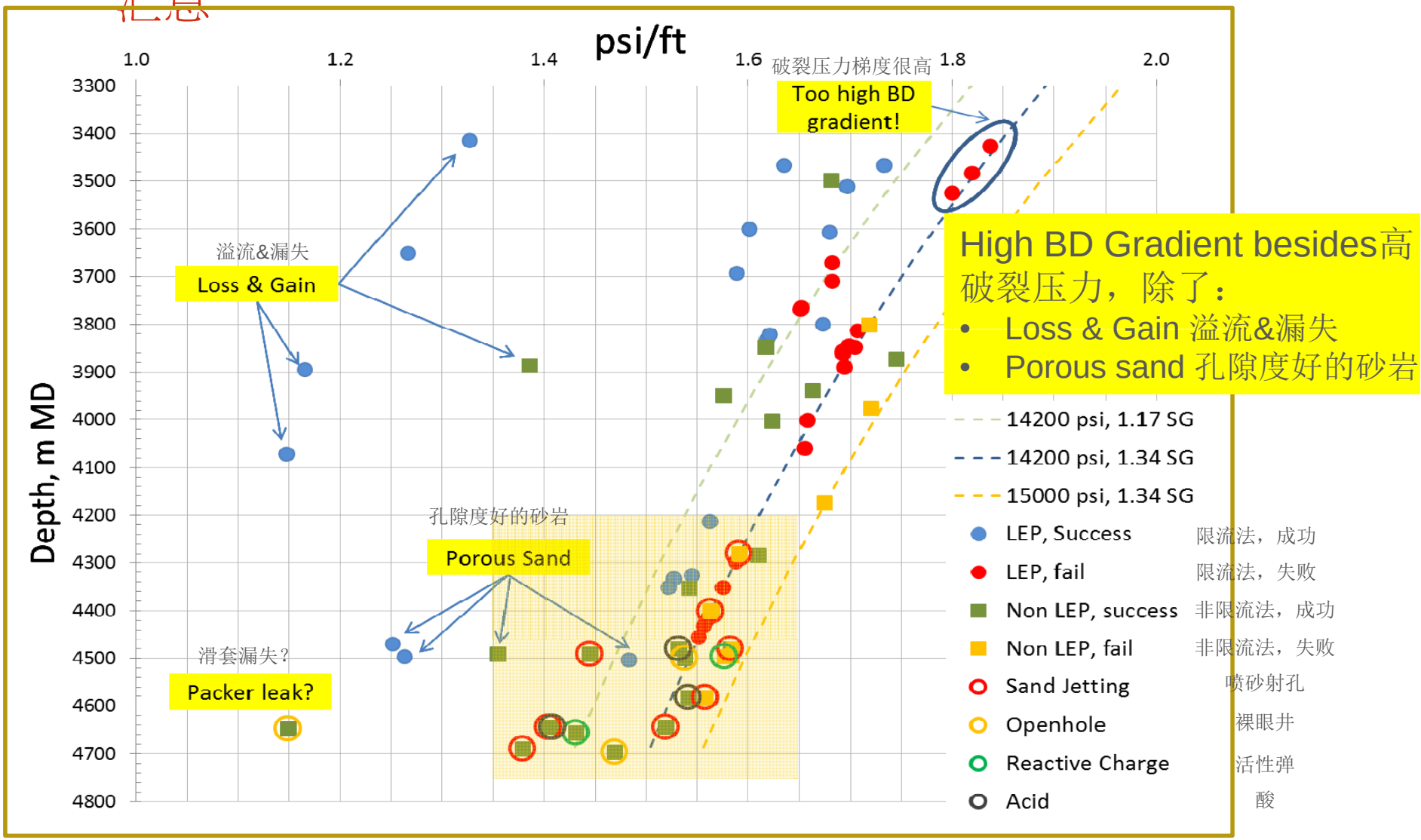
2. Casing gun, depth 4490-4495 m, 4496-4500, 11 holes/m, 0.28 EHD, 60 degree phasing. Trialed 11 pumping cycles, no breakdown at pump limit 14,800 psi (1.58 psi/ft) 射孔枪，11次循环起裂，未能破裂

3. Sand jetting, depth 4487-4496 m, 8 holes/m, 0.37 EHD, 60 degree phasing. BD gradient: 1.44 psi/ft 喷砂射孔

The 3rd BD trial Pumping curve- after sand jetting

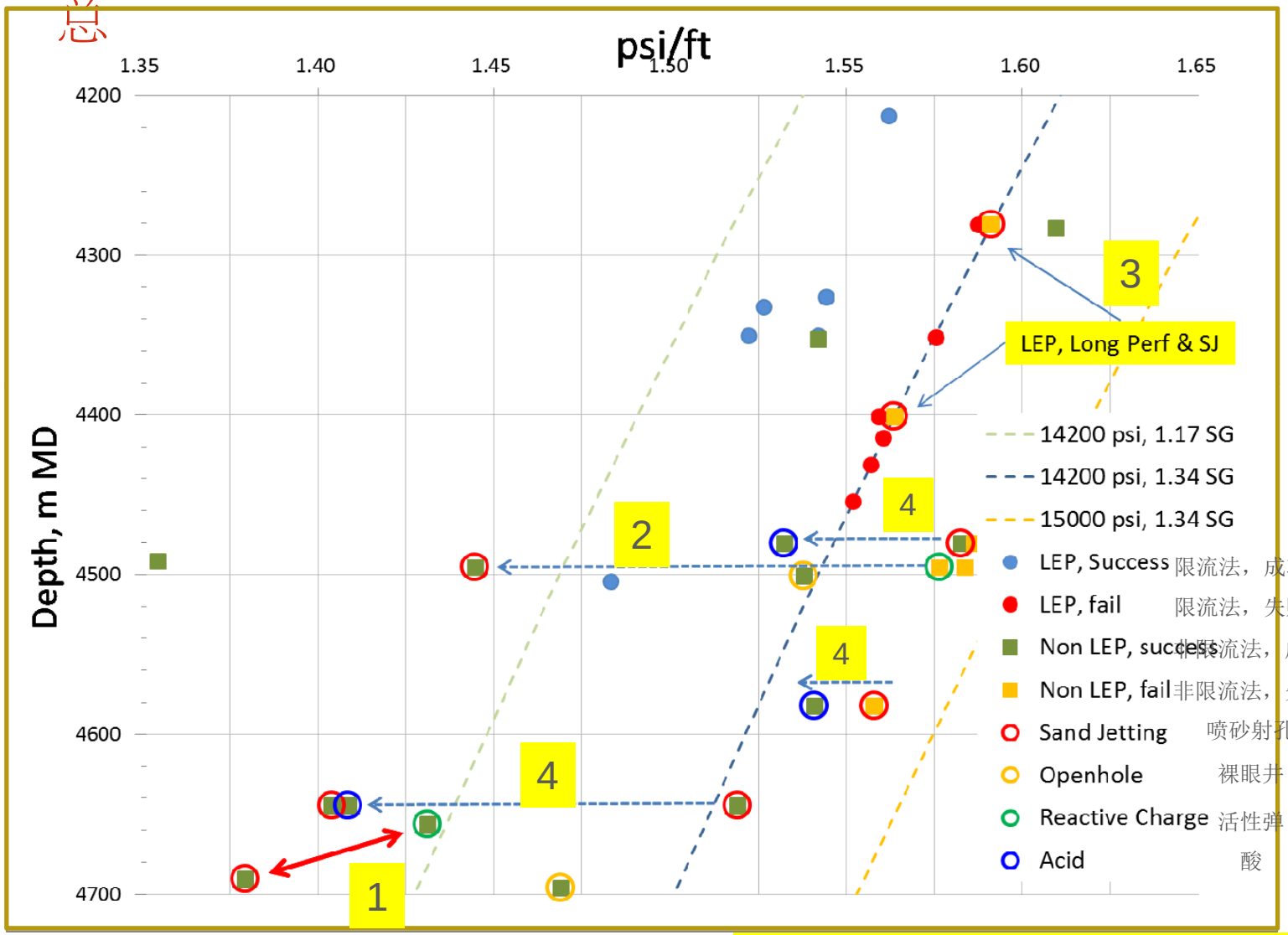


BREAKDOWN GRADIENT of ALL ATTEMPS 破裂压力梯度汇总



Some very high BD pressure when perforation using LEP
限流法射孔段有些是非常高的破裂压力

BREAKDOWN GRADIENT of ALL ATTEMPS破裂压力梯度汇总



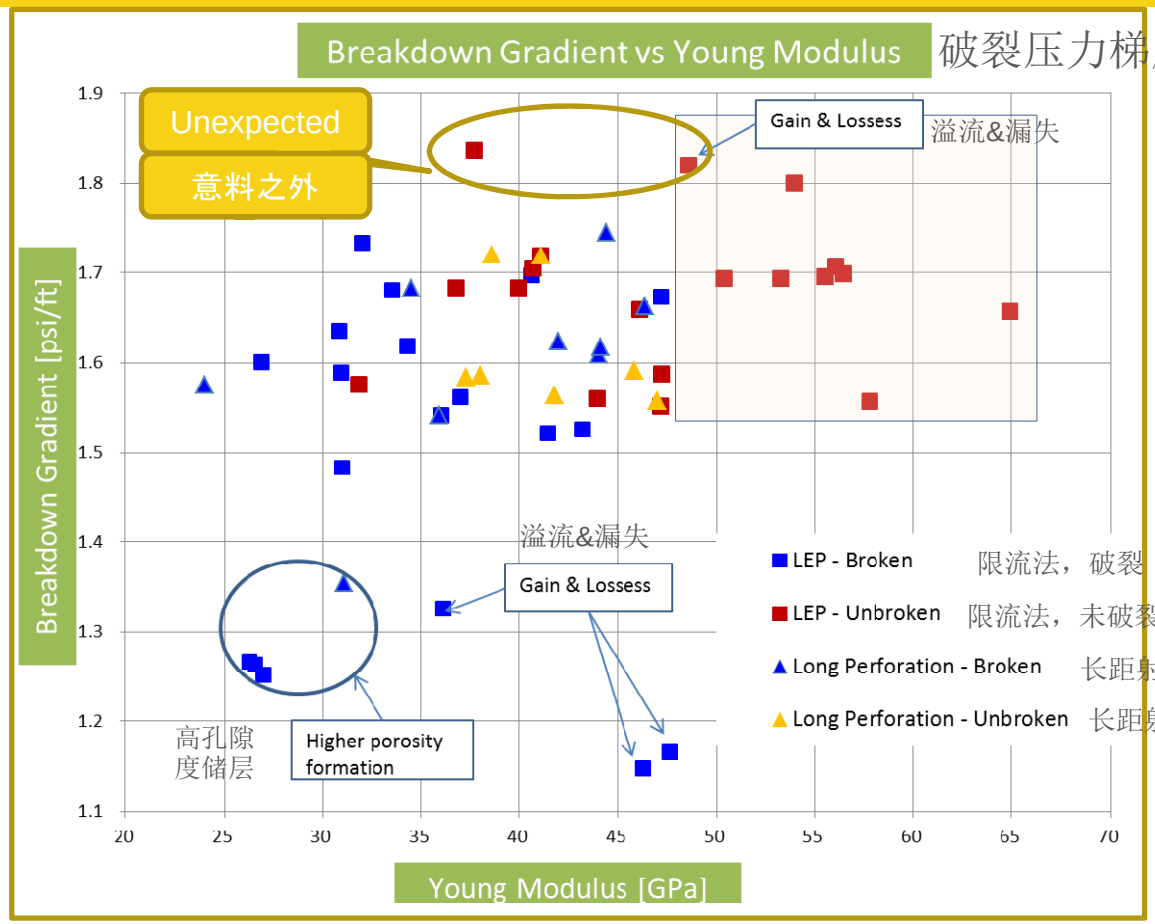
3. LEP, Long Perforation & Sand Jetting were fail. 限流法，长距射孔，喷啥射孔均失败

4. Spot acid across perforation reduce the BD gradient & increase the rate to allow proppant frac注酸降低了破裂压力梯度，提高了泵注排量使加砂成为可能

1. Sand Jetting has lower BD Gradient vs Reactive Charge at same sand 在用一砂体，喷砂射孔的破裂压力比活性弹低

2. Sand Jetting BD the formation that was fail by Long perforation & Reactive Charge 喷砂射孔能破裂长距射孔&活性弹不能破裂的地层

LEP vs Long Interval perforation 限流法 VS 长距射孔



- Success ratios of formation breakdown of Limited entry perforation and long interval perforation are similar (13/24 vs 8/15) **限流法和**长距射孔的成功率相近
- Some unexpected fail to breakdown in LEP that may be caused by miss depth during perforation or inaccuracy drilling depth **限流法中有些意料之外的未破裂有可能是因**为射孔定位或钻井深度的不精确

Conclusion

- Mother nature of the formation play the key role in breaking down the formation地层本身的属性在破裂地层中扮演了关键角色
  - —Breakdown is not an issue in Fractured tight and porous sand intervals在裂缝发育的致密地层和孔隙好的砂岩地层里，破裂地层不是问题
  - —Besides the above features, breakdown gradients are mostly high in the range of 1.37-1.75 psi/ft. 除了有上述特性的地层外，破裂梯度一般比较高，在1.37-1.75的范围
  - —Breakdown issues were predominantly encountered in the tight Xu2 SSt and the Xu4 Conglomerates破裂问题集中发生在致密的Xu2砂岩层和Xu4砾岩层。
- Compare to LEP, Longer perforation ensure that the target interval is perforated to compensate the perforation, logging and drilling depth accuracy 相比于限流法，长距射孔能保证射孔段包括目的层，防止射孔、测井、钻井的定位精度的影响
- Limited entry 60 degree phasing shows slightly better breaking down formation compare to 0 degree phasing, possibly due to the lower tortuosity限流法，60度相位比0度相位破裂地层的情况要稍好一点，可能是因为弯曲摩阻要低一些
- Reactive charge shows mixed success (1 success and 1 fail) and so far showed worse than Sand Jetting活性弹的成功情况不能确定（1成功，1失败），目前为止的结果还是不如喷砂射孔好
- Encouraging result from Sand jetting by breaking down unbroken trials by other perforations but still encountered some failure to propagate the fracture/ establish rate. Need to combine with acid to remove near wellbore damage in certain type of formation or well condition.喷砂射孔的结果令人鼓舞，它能破裂一些其他射孔方式不能破裂的地层，但是在延伸裂缝和建立排量