Geomechanics for Unconventionals Series, Vol V:

Stress Shadows Explained:
What It Is, What It Isn't, And Why You Should Care

By Dr. Neal B. Nagel

Introduction

Much is now made about "Stress Shadows" (SSs) and its impact on hydraulic fracturing. In fact, many (most?) of the major commercial hydraulic fracturing models are reported to have the ability to calculate and account for SSs. Unfortunately, there is no standard definition of SSs and, as a result, there is much confusion over what it is, what it isn't, and, most importantly, why it can potentially have a significant impact on hydraulic fracturing operations.

Stress Shadows Defined

In the field of mechanics (where geomechanics is, in reality, a special form of mechanics with pore pressure), it is a fundamental axiom (for elastic behavior) that stress causes deformation – and deformation causes stress. Simply put, when the stress acting on a body is changed the body will deform (or, potentially, fail). Equally important, if this same body is deformed in some way, the stress within it will change.

Hydraulic fractures (HFs) form because the injection rate exceeds the flow capacity of the formation. Because the injection volume cannot be accommodated, the injection pressure rises (this is actually a very important concept – during HF operations the injection rate can be controlled but the injection pressure is a result of the injection rate - e.g., friction - and the flow capacity of the formation), which omni-directionally presses on the wellbore and completion (e.g., perforations in a cased-and-perforated completion or the wellbore wall in an openhole completion). As the well pressure deforms the perforation or wellbore, it changes the stress within the formation. The "breakdown" pressure is that pressure within the wellbore when the pressure creates a large enough stress in the formation to cause it to fail. And rock, often being far weaker in tension than in shear, will tend to fail in tension first (i.e., initiate an HF). So an HF forms because injection pressure, whose increase is due to limited flow capacity in the formation, deforms the formation, which changes the stress in the formation leading to failure.

HFs propagate in a similar manner. When the injection rate entering an initiated HF exceeds the leakoff rate (the loss rate of fluid from the HF into, perhaps, the matrix pore structure or natural fractures), the injection pressure rises, which causes: 1) the HF to deform and increase in width to accommodate the new volume of fluid; and/or 2) the formation to fail (again, often in tension) at the leading edge of the HF and the HF to increase in dimension (length and/or height) to accommodate the new volume of fluid. The deformation of the HF, both the changing width along the body of the HF and the increased dimension (length and/or height) of the HF along the leading edge cause a change in the stress field in

the formation. “Stress Shadows” is the colloquial term for these stress changes induced by the formation deformations caused by the HF.

Stress, in its most complete form, is a nine-component tensor (with six independent values). Stress is also commonly resolved into its normal stress components (those acting perpendicular to a surface) and shear stress components (those acting parallel to a surface). Being a tensor, any arbitrary orientation can be chosen to define the six independent (three normal and three shear) values that define stress acting at a point in a formation; however, in one orientation, the shear stresses go to zero and stress can be defined solely by the three normal stress magnitudes (as well as the orientation). The normal stresses in this particular orientation (where the shear stresses are zero) are called principal stresses. Correctly, these are labeled (in descending magnitude) the S1, S2, and S3 stresses. Colloquially, these are called the vertical stress, Sv, the maximum horizontal stress, SHmax, and the minimum horizontal stress, Shmin (and in a normal faulting environment, Sv > SHmax > Shmin).

Recall that the injection pressure, which is often principally a result of an injection rate greater than the flow capacity of the formation, acts omni-directionally. As a result, injection pressure will act to deform the rock at the lowest possible energy regardless of orientation. This means, for example, that an HF will open against the S3 principal stress as it is the lowest stress and would require the least injection pressure. In a normal faulting environment, this means the HF will propagate towards SHmax and open against Shmin (because this orientation, all other things being equal, will require the least injection pressure). And “Stress Shadows”, then, is at least partially defined by the HF deformation in the Shmin direction and the resulting increase in Shmin.

The common perception of “Stress Shadows” is that it is synonymous with the increase in Shmin due to an HF. Unfortunately, this is potentially a significant oversimplification. Note that an HF causes not only deformation in the width of the HF, but also deformations at the HF leading edge. Ahead of the physical HF tip, Shmin is reduced (and, in fact, goes into tension at the micro-location of the HF tip). In addition, the HF tip generates significant shear stresses. Finally, due to the Poisson’s ratio effect, the increase in Shmin due to the change in HF width also causes a local increase in both SHmax and Sv. In summary, the “Stress Shadow” may be dominated by the increase in Shmin along the body of the HF, but other important normal and shear stress changes are also induced by an HF.

Stress Shadows from a Single Hydraulic Fracture

Figure 1 shows simulated contours of the change in Shmin from an HF. In this case, the half-length of the HF is 300m within a model of 1000m in size. The model has been cut horizontally at the wellbore (mid-line of the vertical HF) and vertically along the wellbore and along the length of the HF in order to highlight 3D changes in the formation. Note also that the white region is a region with stress greater than the color bar.

Several features are evident in Figure 1. First, the change in stress can reach a significant distance from the HF. As shown, Shmin is increased to more than 50 psi as far as 300m away from the HF along the horizontal wellbore. In addition, the change in Shmin occurs almost exclusively behind the tip of the HF; there is little change in Shmin in the region beyond the tip of the HF. Finally, note the non-planar depth of the change in Shmin behind the HF; the 50 psi contour is farthest from the HF at the wellbore and gets closer nearer to the HF tip.

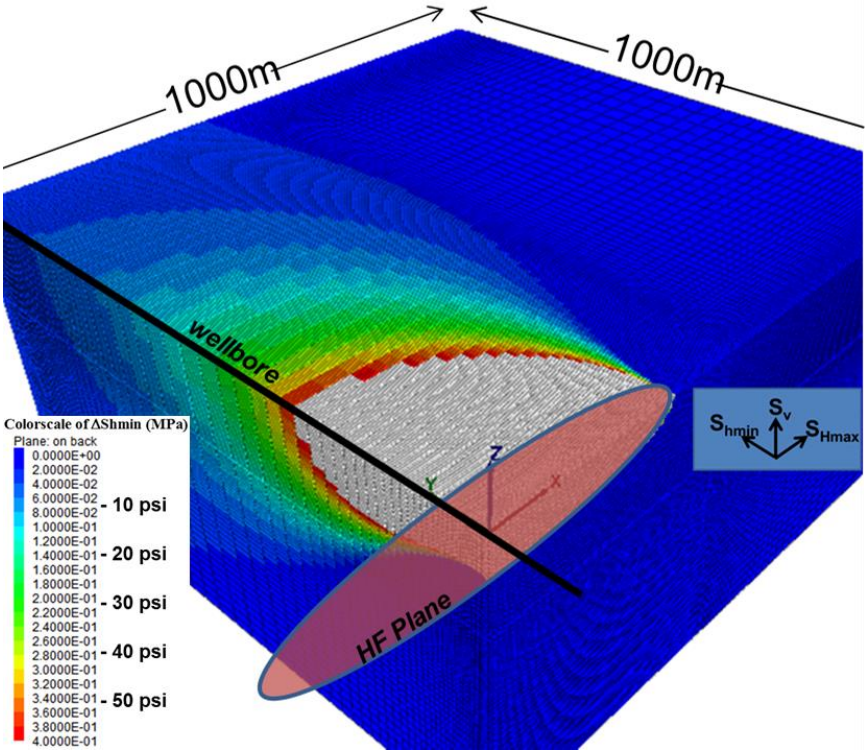

Figure 1: Contours of the change in Shmin ("Stress Shadow") from a single HF.

Figure 2 shows a clearer picture of the non-planar behavior of the change in Shmin. As shown, the greatest increase in Shmin occurs just below the wellbore and then rapidly decreases towards both the left and right tips of the HF (as well as towards the upper and lower tips). Note that the model has again been cut horizontally along the wellbore and, in this case, vertically along the plane of the Stage 1 HF.

The change in Shmin reflected in Figure 2 corresponds to the deformation of the Stage 1 HF. That is, the increase in Shmin is greatest where the Stage 1 HF is widest and, as the HF aperture decreases to zero at the HF tips, the increase in Shmin also decays to zero at the tips of the HF. This is fundamental mechanics – the variation in the deformation of the HF along its length (its aperture) results in a similar variation in the change in Shmin along its length.

This is a critical understanding about Stress Shadows: both the magnitude and spatial variation of the increase in Shmin from a single HF correspond directly to the HF aperture. And anything that causes a change in the aperture (e.g., a change in the injection pressure) will cause a change in the increase of Shmin. More importantly, as HF aperture changes during HF closure on proppant, the Stress Shadow also changes. Thus, the Stress Shadow can be dynamic.

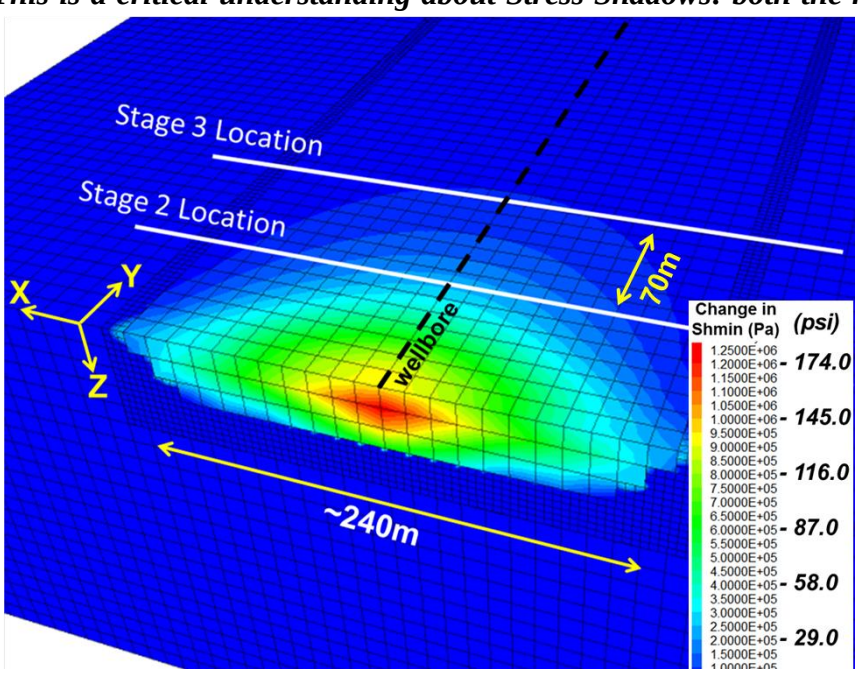

Figure 2: Detailed contours of the change in Shmin from a single HF.

Figure 2 also introduces the potential source of HF curvature reported in some microseismic data sets. Assume that the Stage 2 HF initiates at the wellbore for the Stage 2 Location shown in the

figure. Recall also that an HF propagates along the path of least resistance. The Stage 2 HF will initially come from the wellbore along the prescribed Stage 2 Location line; however, the lower-stress, path-of-least-resistance for the Stage 2 HF will be to grow towards the lower stress environment nearer to the prescribed Stage 3 Location and, as a result, the Stage 2 HF will not be parallel to the Stage 1 HF but will tend to grow away. ***This is also a critical understanding about Stress Shadows – the increase in Shmin will affect the trajectory of subsequent HFs that might propagate within the Stress Shadow region from a previous HF.***

The magnitude and depth of the increase in Shmin due to an HF is a function of magnitude of the HF aperture (which is a function of the net pressure – where net pressure is the injection pressure inside the HF minus the original Shmin) as well as the HF shape. The three plots in Figure 3 show profiles of the increase in Shmin, SHmax, and Sv as measured at the wellbore (e.g., the wellbore position shown in Figures 1 and 2) away from the HF as a function of the HF height for an HF much longer than it is tall.

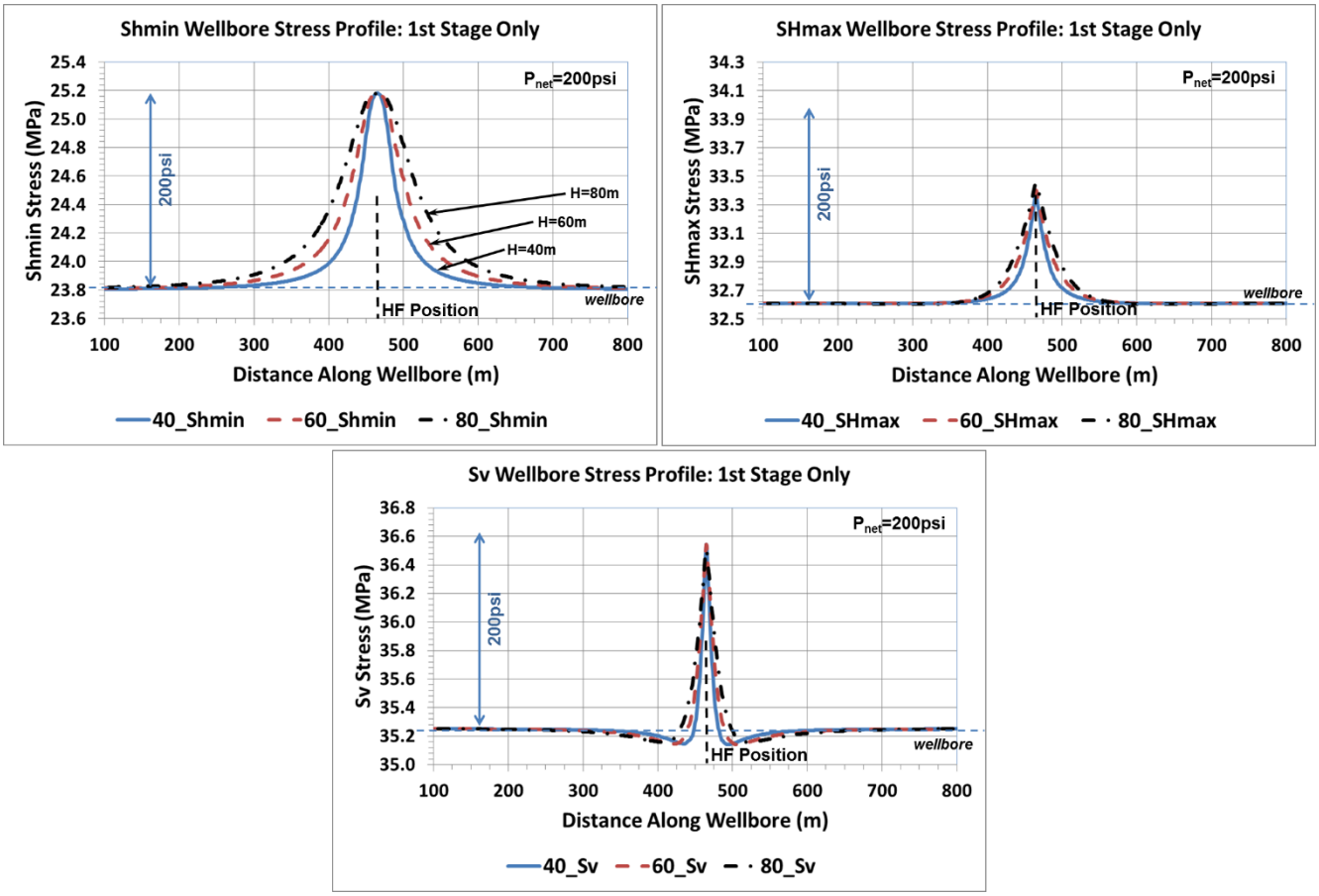

Figure 3: Plots of the change in principal stresses due to a single HF. UL: the increase in Shmin. UR: the increase in SHmax. LM: the increase in Sv.

The upper left (UL) plot shows the profile of Shmin along the wellbore on either side of an HF for HF heights of 40, 60, and 80m. Note that HF net pressure was set at 200 psi. As shown, as the HF gets taller (for a constant net pressure), the maximum value of the increase in Shmin is unchanged (and equal to the net pressure) but the depth of the change in Shmin into the formation away from the HF increases. The upper right (UR) plot shows the profile of SHmax along the wellbore on either side of an HF for HF

heights of 40, 60, and 80m. The lower middle (LM) plot shows the profile of Sv along the wellbore on either side of an HF for HF heights of 40, 60, and 80m. The changes in SHmax and Sv are caused by the Poisson's ratio effect, which, again, is defined as orthogonal formation deformation due to an applied axial stress (in this case, the increase in Shmin due to the HF aperture). However, recall that rock deformation (and failure) is controlled by the effective stress (and the Stress Shadow - the increase in Shmin - is a total stress change). Consequently, the resulting changes in SHmax and Sv are a function of: 1) the increase in Shmin; 2) the formation Poisson's ratio (where a higher PR value will lead to greater SHmax and Sv increases); and 3) the formation pore pressure (where for overpressured formations the effective stresses are lower and the increases in SHmax and Sv are less). Comparing the three plots in Figure 3, it is clear that the effect on Shmin dominates over the effects on SHmax and Sv.

Other critical learnings about Stress Shadows include: 1) all three principal stresses (Shmin, SHmax, and Sv) are affected by Stress Shadows; 2) the magnitude and depth of the changes is related to HF aperture (which is a function of net pressure and fracture height when the HF is much longer than it is tall); and 3) changes in SHmax and Sv are also controlled by Poisson's ratio and formation pore pressure.

Since the increase in Shmin is controlled by the net pressure and HF dimensions, which can be fairly large, the increase in Shmin could be as high as several thousand psi. In the event that the increase in Shmin is greater than the difference between Shmin and SHmax (and the increase in SHmax due to the Poisson's ratio effect) – and for that matter, if the increase in Shmin is greater than the difference between Shmin and Sv – then the principal stresses may completely rotate as shown in Figure 4. In the figure, the blue-green crosses represent the orientation of the SHmax (green) and Shmin (blue) stresses. Note that the red extension represents the vertical stress. Within the ~ 7m shaded region note that the crosses have completely rotated and that the Shmin stress is aligned parallel to the HF (which runs along the lower right side of the model) rather than be aligned perpendicular as they are ahead of the HF tip and deeper into the formation away from the HF.

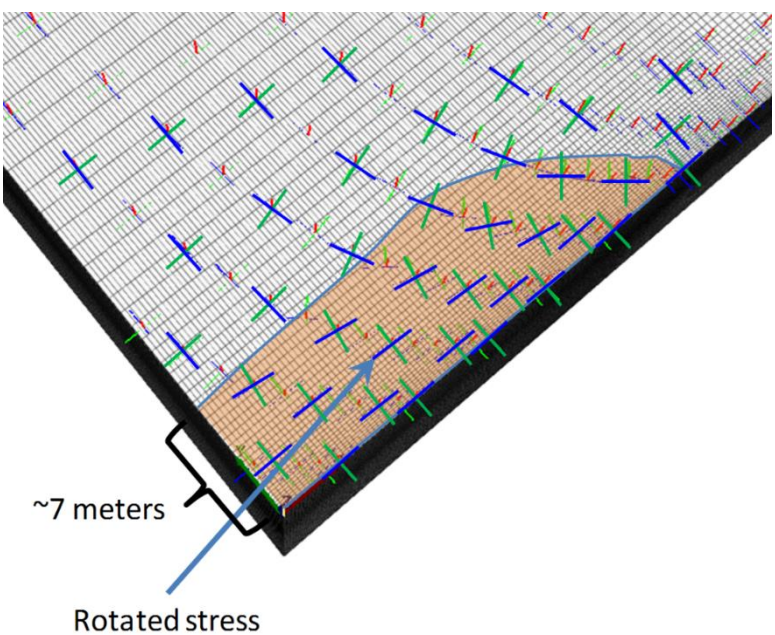

Figure 4: Stress tensor crosses showing the rotation in Shmin and SHmax near an HF. Blue is the orientation of Shmin and green the orientation of SHmax.

If a new HF was initiated within the shaded region in Figure 4, the HF would, at least initially, propagate perpendicular to the original HF and run parallel to the wellbore (creating a longitudinal, rather than transverse, HF). This effect has been shown in published microseismic data (in, for example, the Vaca Muerte in Argentina).

What about the original HF. Would the rotation shown in Figure 4 not cause the original HF to also rotate? In all likelihood, the original HF would not rotate because any loss of fluid into the rotated direction would tend to decrease the magnitude of the increase in Shmin and reduce or eliminate the stress rotation.

Another critical learning about Stress Shadows is that, depending upon net pressure and fracture dimensions (which control HF aperture), the increase in Shmin may cause it to increase in magnitude and be greater than SHmax (so Shmin and SHmax essentially swap orientations). As a result, Stress Shadows from one HF may cause subsequent HFs to propagate longitudinally along the wellbore. This effect will be controlled both by the magnitude of the increase in Shmin as well as the original difference between Shmin and SHmax (with a greater likelihood of the rotation occurring when the horizontal stresses are nearly isotropic).

Stress Shadows from Multiple Hydraulic Fractures

When multiple HFs propagate from a horizontal wellbore, the Stress Shadows from the multiple HF may interact as shown in Figure 5 (which is the two HF version of Figure 1). As the second HF grows, the contours of the increase in Shmin interact <u>and add together</u>.

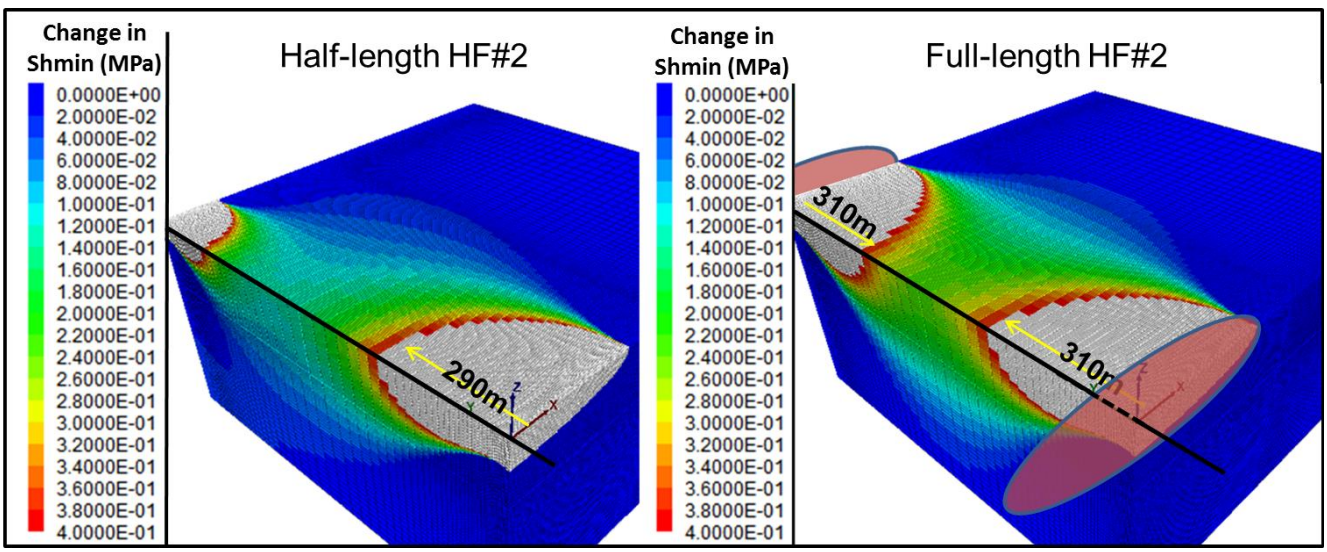

Figure 5: Contours of the increase in Shmin between two HFs.

The three plots in Figure 6, similar to those in Figure 3, show profiles of the increase in Shmin as measured at the wellbore (e.g., the wellbore position shown in Figures 1, 2, and 5) away from the HF as a function of the HF height for an HF much longer than it is tall and as a function of HF spacing. In the upper left (UL) plot, Shmin profiles along the wellbore are shown for HFs with heights of 40, 60, and 80m for a spacing of 56m between the two HFs. In the upper right (UR) plot, Shmin profiles along the wellbore are shown for HFs with heights of 40, 60, and 80m for a spacing of 70m between the two HFs. In the lower middle (LM) plot, Shmin profiles along the wellbore are shown for HFs with heights of 40, 60, and 80m for a spacing of 154m between the two HFs.

What should be obvious from Figure 6 (particularly in the UL and UR plots) is that the magnitude of the increase in Shmin from Stress Shadows increases as HF stages get closer for a given HF height. In the

LM plot at 154m HF spacing, as the HF height increases, the inter-HF region experiences a significant increase in Shmin but the peak value of Shmin at the HFs is still essentially 200 psi (the net pressure). However, in the UL plot at 56m HF spacing, the peak value of Shmin for an HF height of 40m is about 20% greater than for a single HF (Figure 3) and the peak value of Shmin for an HF height of 80m is more than 60% greater than for a single HF. Figure 7 shows the increase in Shmin (measured at the wellbore) for both constant HF stage spacing and irregular HF stage spacing examples.

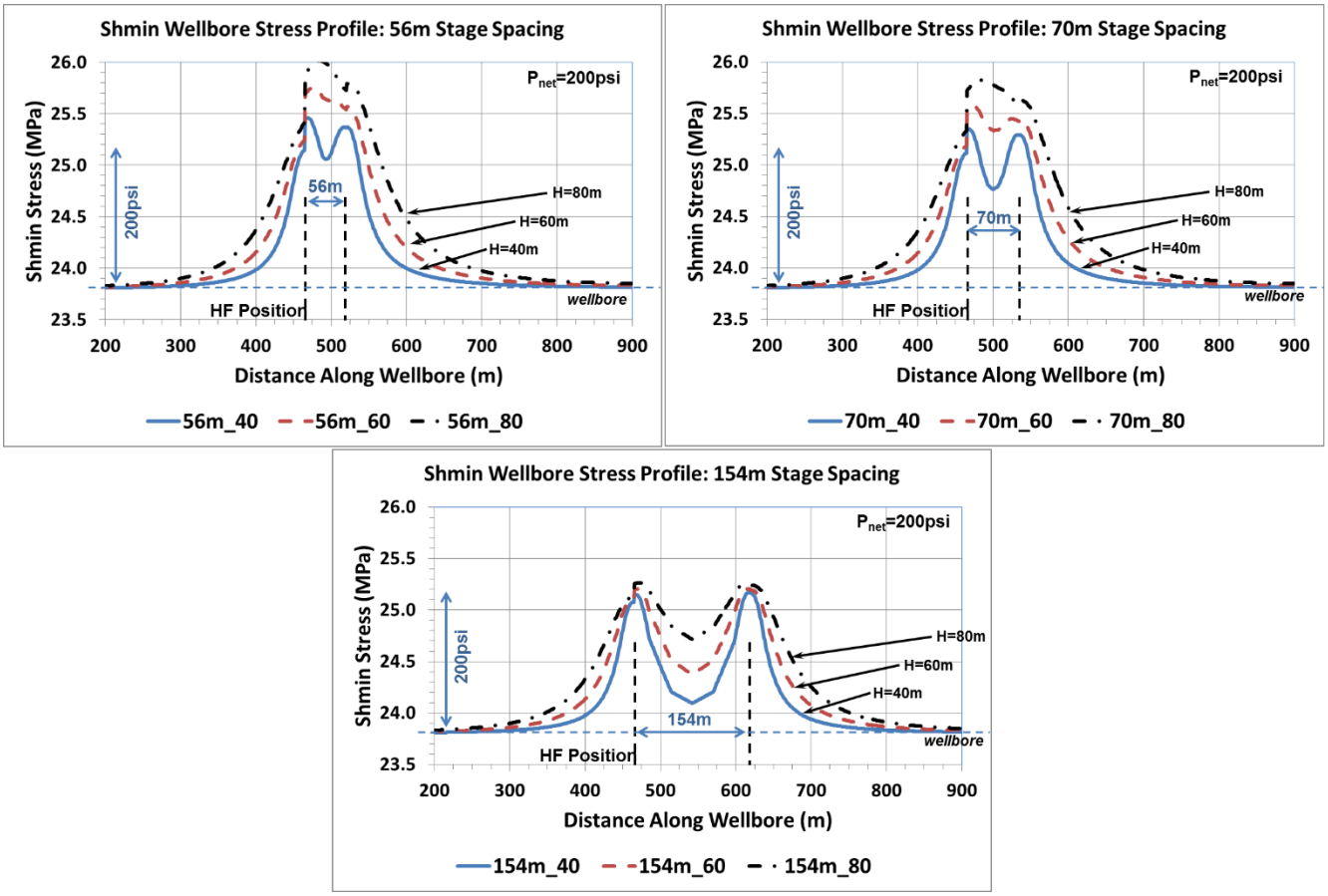

Figure 6: Plots of the increase in Shmin at the wellbore as a function of HF height and HF spacing.

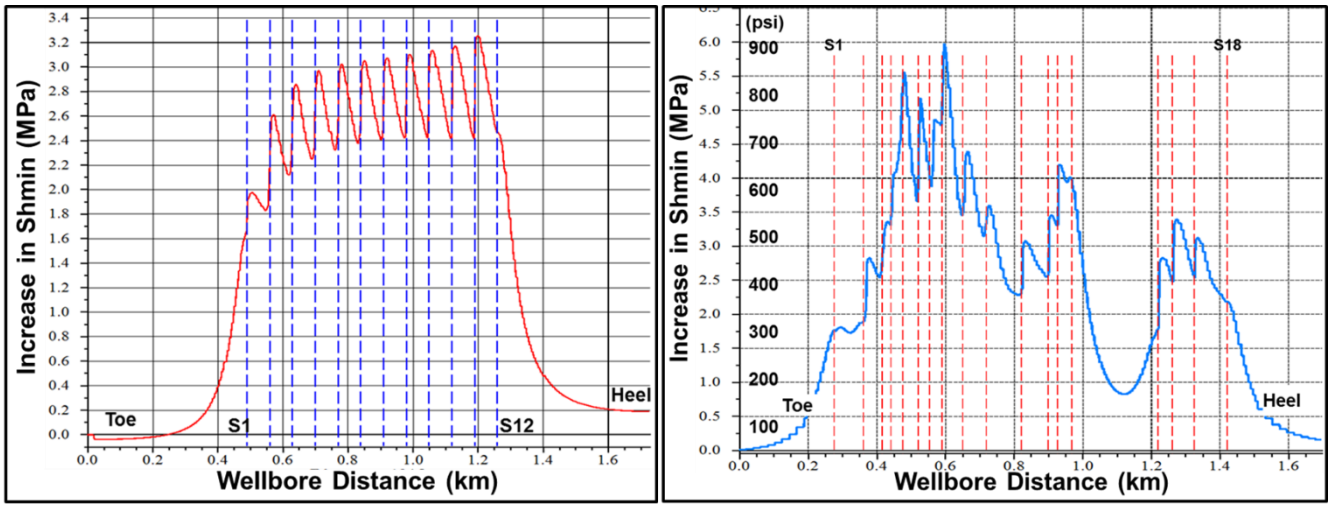

Figure 7: Profiles of the increase in Shmin along the wellbore for regular HF spacing (left) and irregular spacing (right).

As shown in Figure 7, when the HF spacing is regular (70m for the well profile in the left plot) the increase in Shmin is rapid over the first few HF stages and then the rate of increase begins to level off (though Shmin is still increasing even by the 12th HF stage (S12)). In stark contrast, when the HF spacing becomes irregular (whether planned or not), the increase in Shmin becomes more erratic and may almost disappear completely (as occurs between the 14th and 15th HFs in the right plot in Figure 7).

The increase in the Stress Shadow (the increase in Shmin) has been confirmed in many field examples. Figure 8 shows published (from Stanford) ISIP data (the best proxy for Shmin in most horizontals) for several field cases. While for two of the wells the increase in ISIP from toe to heel was on the order of 700 psi, note that for several wells the increase was as much as 1500 psi or more.

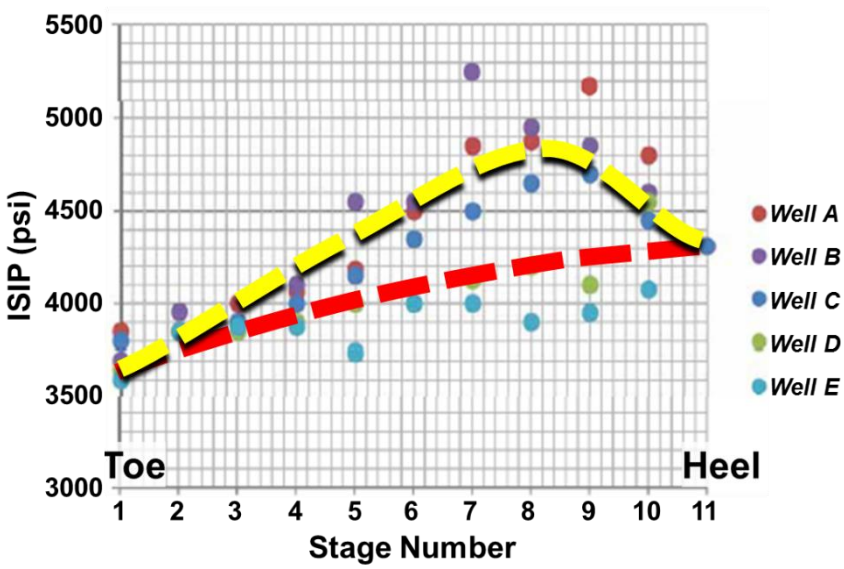

Figure 8: Field-measured changes in ISIP due to Stress Shadows.

Critical learnings about Stress Shadows are that: 1) the increase in Shmin can be additive when HFs are close enough together; 2) the increase is a function of HF height and HF spacing; 3) irregular HF spacing (planned or unplanned) can result in very irregular increases/decreases in Shmin; and 4) field data has not only confirmed the existence of Stress Shadows (the increase in Shmin) but has shown that the additive effect of close HF spacing can result in an increase in Shmin of several thousand psi from toe to heel in a horizontal wellbore.

Shear Stresses from Hydraulic Fractures: A Critical, Often Overlooked, Effect

At the edge of an HF, shear stresses are generated rather than changes in the principal stresses. These shear stresses are created around the entire edge of the HF, but vary in their orientation of greatest shear as shown in Figure 9. In the left plot of the figure, contours of the shear stresses in the x-y horizontal plane are shown from the leading tip of the HF. The right plot in Figure 9 shows contours of the shear stresses in the vertical y-z plane from the lower HF edge (and upper if the model were not cut horizontally along the wellbore). These shear stresses are important both because they are a primary cause of many of the microseismic events seen in field data (as reported by Warpinski) but also because they can fail and open natural fractures and weakness planes to fluid pressure changes.

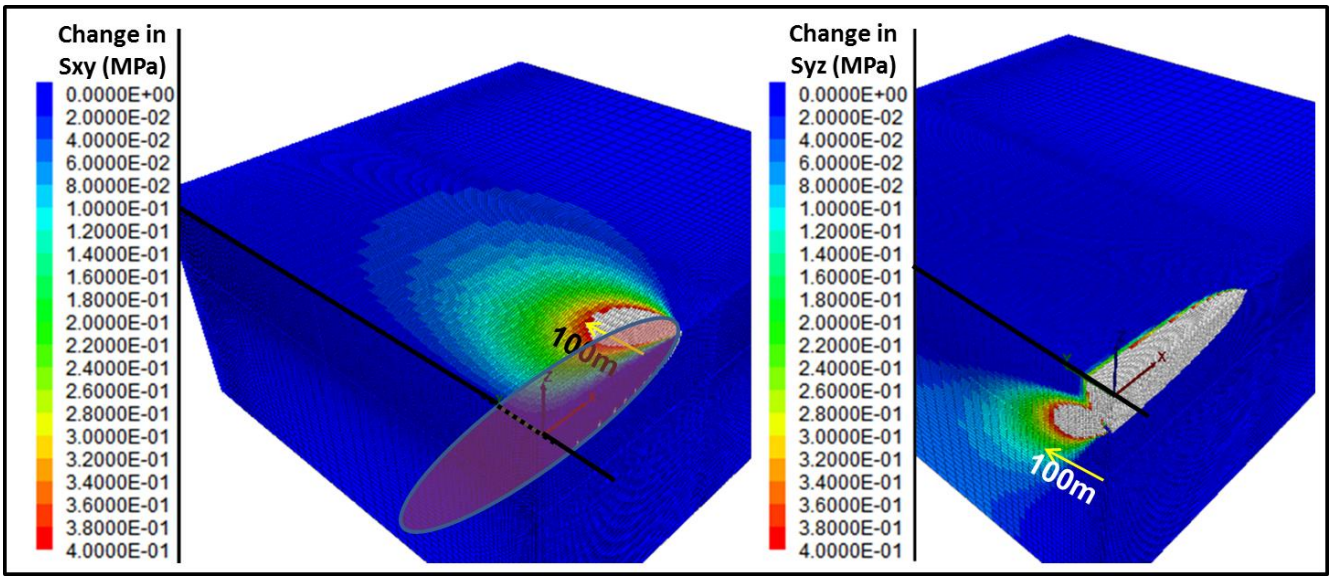

Figure 9: Contours of the Sxy shear stresses from the horizontal leading edge of an HF (left) and the Syz from the lower edge (right).

Figure 10 shows a more detailed view of the contours of shear stress from the vertical tip of an HF (left) and from the horizontal leading tip of an HF (right). The contours represent the shear stress normalized

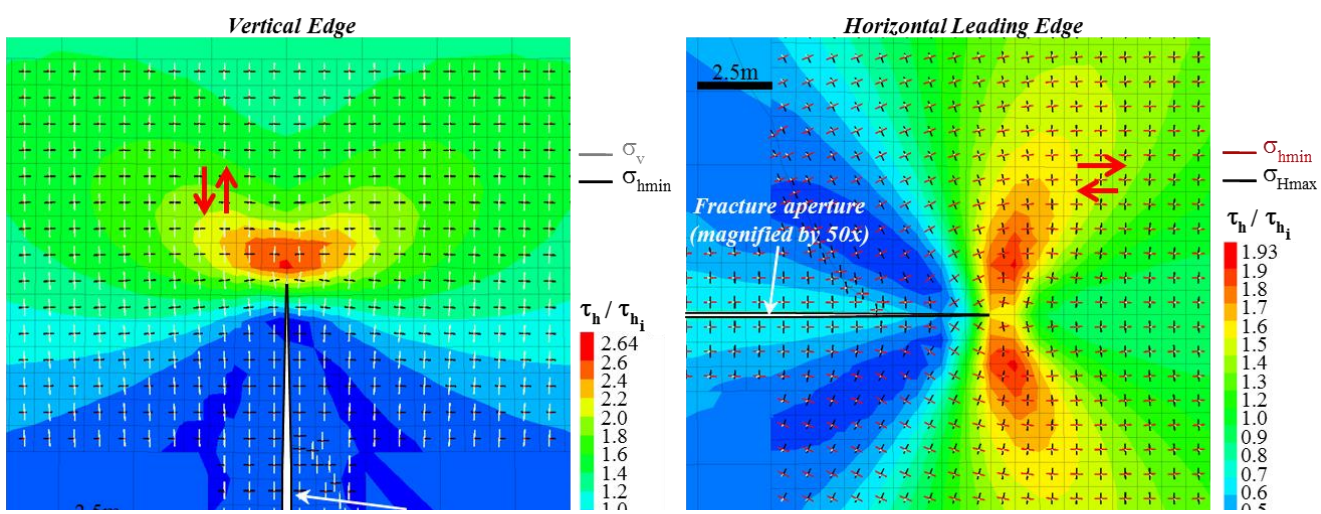

Figure 10: Normalized shear stress contours from the vertical edge of an HF (left) and the horizontal tip (right). Shear is normalized to the original in-situ shear stress. Warm colors represent regions of increased shear while cooler colors are regions of decreased shear.

to the initial values (the in-situ shear stress before the HF is created). Warm colors mean an increase in shear stress while cool colors represent a decrease. Note that the shear stress increases ahead of the tip (for both the vertical and horizontal tips) while it decreases behind the tip (which is due to the increase in Shmin). The contours of shear stress clearly suggest that certain locations and certain orientations will be subjected to the greatest increase in shear stress due to the HF. This is, for example, an important point that is often overlooked during moment tensor analysis of microseismic field data because the results of the slippages computed must be compared to the shear stresses generated from the HF (which, again vary in magnitude and orientation around the edge of the HF) rather than simply be compared to the original stress field. That is, it is the overprint of the shear stresses from the HF on the original stress field that causes the slip events and not the original in-situ stress field (as occurs in common earthquake moment tensor analysis).

Just as the principal stresses are affected when multiple HFs are placed in close proximity, so too are the shear stresses. Figure 11 shows the changes in the normalized maximum horizontal shear stress as three HFs are placed in a Zipper Frac configuration. Each of the six plots represents a plan view of the stress contours at the level of wellbore (shown in the white dashed lines). Again, warmer colors represent an increase in shear stress while the cooler colors represent a decrease in shear stress. The HFs are represented by the horizontal grey lines that stretch between the warm-colored lobes. Note that the large blue-colored regions are regions of reduced shear stress.

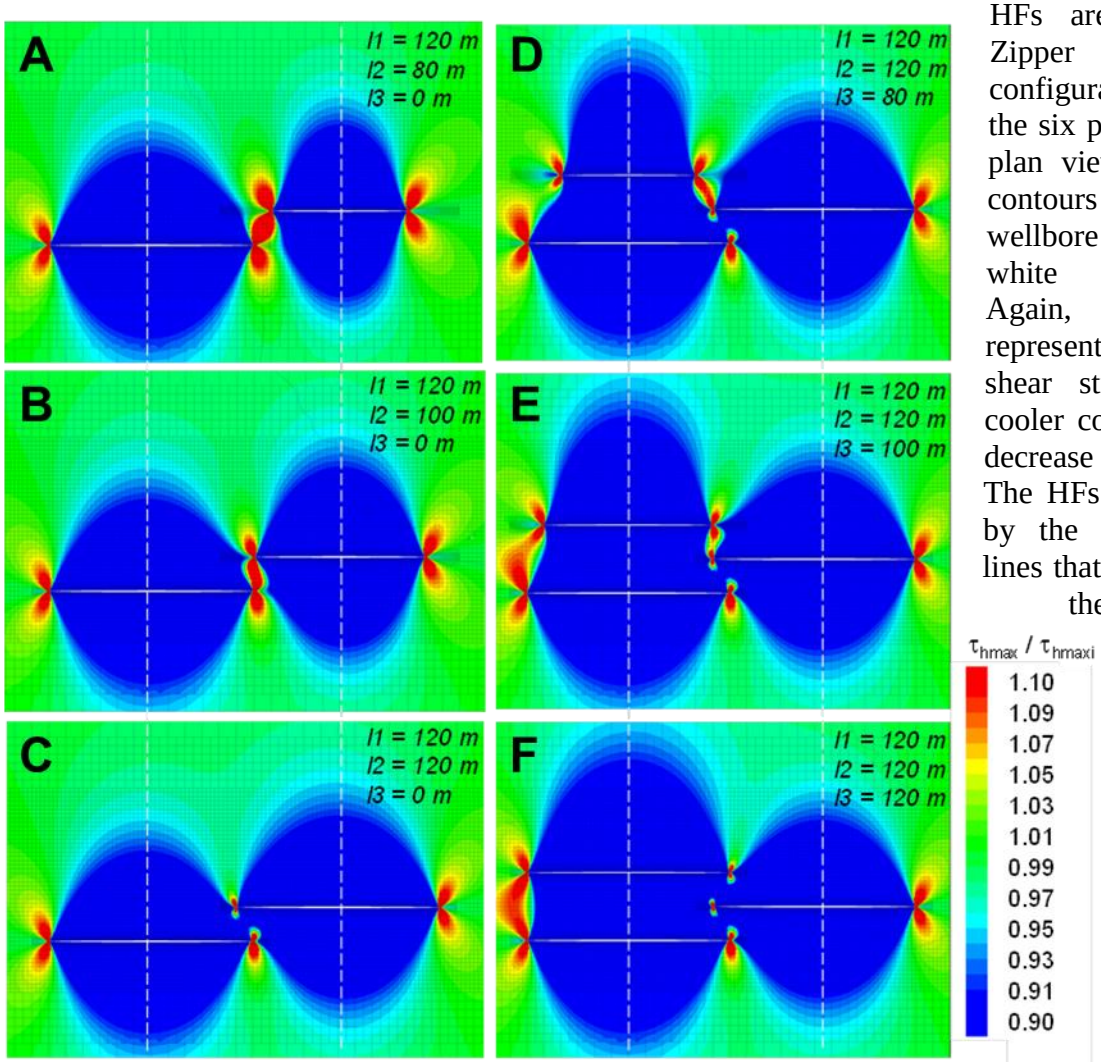

Figure 11: HF tip shear stress development from a three HF Zipper configuration.

In plot A, the first HF (I1) from the left well is complete and 120m in total length. The increase in the horizontal shear stress ahead of the horizontal tip are evident in red. In

addition, the first HF (I2) from the right well is 80m in length. At this position, there appears some amplification of the horizontal shear stress between the right tip of I1 and the left tip of I2.

In plot B, HF I2 is now 100m in length. The amplification in shear stress between the two HFs is gone and the shear stress is perhaps somewhat reduced. By the time HF I2 is 120m in length (plot C), it is clear that interaction between the two HFs has significantly reduced the shear stresses from the overlapping HF tips (while, not surprisingly, the shear from the outer tips is unaffected). Plots D, E, and F show the shear stress development when the second HF from the left well is created. Note the significant reduction in the tip shear as HF I3 develops. In addition, note the amplification of the shear stress on the left, outer edge of I1 and I3.

The creation and influence of shear stresses from HFs is more complicated than can be presented here. However, there are a number of critical learnings about Stress Shadows when considering the shear stresses:

- ***Consideration of Stress Shadows must also account for the generation of shear stresses from the tips of the HF;***
- ***The generated shear stresses have both a magnitude and preferential orientation. Mention of the horizontal, Sxy, or vertical, Szy, shear stresses, for example, are a means to describe the shear stress but these orientations may not be (are often not) the orientation of maximum shear stress;***
- ***The magnitude of the generated shear stresses is a function of HF dimensions, geometry, and net pressure (the shear stresses, like the increase in Shmin, respond to the deformations induced by the HF);***
- ***In both mult-HF stage horizontal wells and multi-well (e.g, Zipper Frac) completions, the interaction of the Stress Shadows can either increase or decrease HF tip shear stresses; owever, the dominate effect is to reduce (and nearly eliminate) tip shear stresses between parallel wellbores.***

Ahead of the HF Tip: The Region of Reduced Compression

While an HF could propagate in shear, it often propagates in tension (called a Mode 1 HF) as, for most cases, the formation is weakest in tension. As a result, the injection pressure must overcome the least principal stress (often Shmin) and the tensile strength of rock. Figure 12 shows an example of the reduction in Shmin ahead of two approaching HFs. Note that these are not regions of tension – rather this is the region of reduced compression ahead of the HF tip. Only the formation immediately at the HF tip goes into tension as an HF propagates.

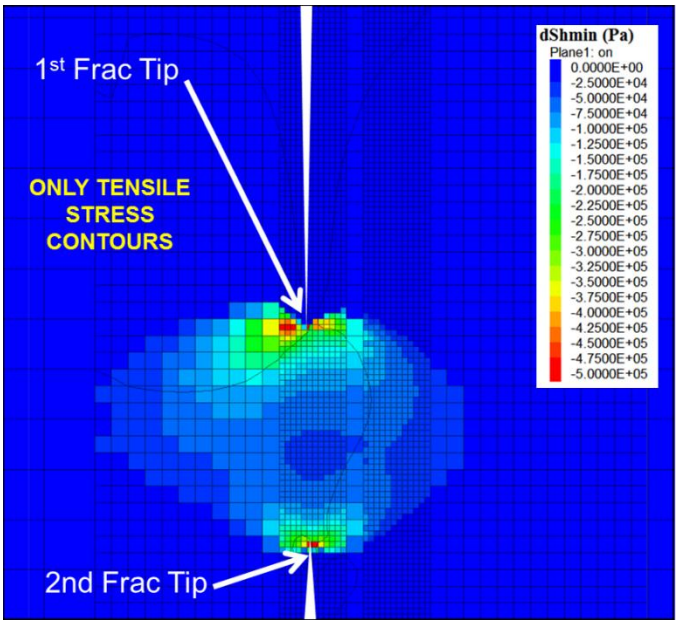

Figure 12: Contours of the region of reduced compression ahead of two approaching HF tips.

The region of reduced compression, though small in size, will tend to attract a propagating HF. All other things being equal, as one wing of an HF reaches a region of reduced compression, this will become the path of least resistance for HF propagation and the HF will tend to grow more in this region. Figure 13 shows the configuration for two HF propagating towards each other as well as the position of the four HF tips (an inner and outer HF tip for each of the two HFs) as the HFs grow in a simultaneous fashion. Once the inner tips of the two HF reach the region of reduced compression, they accelerate towards each other while the outer tips essentially stop propagating. Then, once the tips have passed each other, it becomes easier for the outer tips to propagate and the inner tips essentially stop propagating.

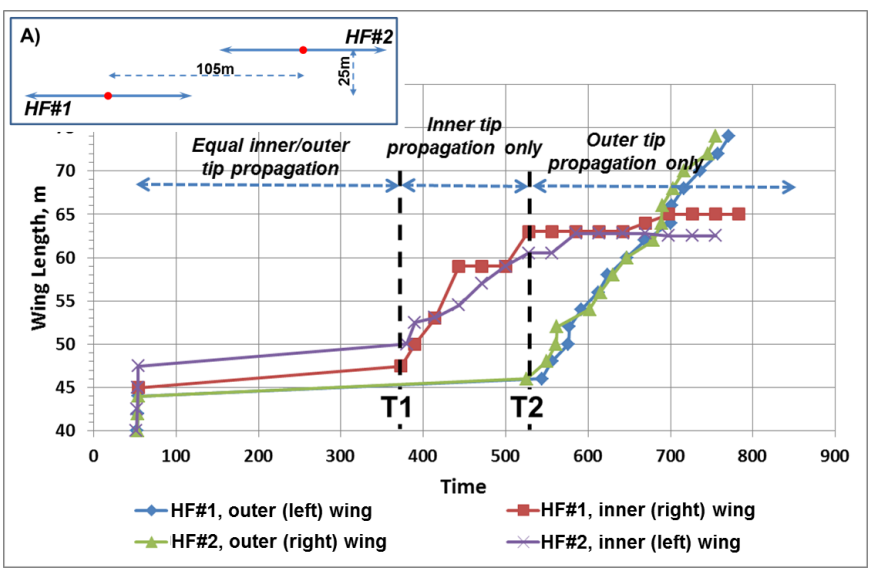

Figure 13: Plot of HF tip growth versus time for two overlapping HFs in a Zipper Frac configuration.

The inset in Figure 13 shows the well configuration with wellbores 105m apart and the spacing offset between HFs of 25m. The HFs were pumped at the same time and with the same rate. Prior to time T1, the inner and outer tips for both HFs grow in a near equal fashion (the slight difference is a trivial modeling artifact). At time T1, the inner HF tips sense the region of reduced compression from the other HF. From time T1 to T2, propagation of the inner tips becomes the path of least resistance for the HFs to propagate while the outer tips essentially stop. At time T2, however, the inner tips now overlap and the increased Shmin behind

the HF tip essentially stops the inner tips from propagating and further propagation is dominated by outer tip growth.

The critical learnings about Stress Shadows is that: 1) ahead of the HF tip there is a small region of reduced compression; 2) the region of reduced compression creates a favorable path for subsequent HFs to propagate towards and in; and 3) the location and size of the reduced compression must be accounted for when HFs propagate towards each other from separate wellbores.

Stress Shadow Effects on HF Propagation from Parallel Wellbores

Figure 14 shows the progression in the change in Shmin and tip shear stresses as three HFs are created in a Zipper Frac configuration. In plot A, a single HF has been created from wellbore #1. The left image shows the contours of the change in Shmin (both the increase behind the HF tip and the decrease ahead of the tip). The right image shows the contours of horizontal tip shear stress. In plot B, the first HF from the wellbore #2 has been pumped with the same volume and rate as the first HF from wellbore #1. As shown, the HF tips overlap and the HF from wellbore #2 appears to be slightly longer towards wellbore #1 than away. In addition, the first HF from wellbore #2 is longer than the first HF from wellbore #1 (even though the same fluid volume was pumped). The region between the wellbores appears to show a reduce area of shear, but, perhaps, an amplification of the shear near the tip of the first HF from wellbore #1. In plot C, the second HF from wellbore #1 has been pumped (with, again, the same rate and fluid volume). It is clear in the left image that the second HF from wellbore #1 is much longer than the previous two HFs and it shows significant growth to the left, away from wellbore #2. The right image in plot C again shows the significantly reduced shear stresses in the region between the two wellbores.

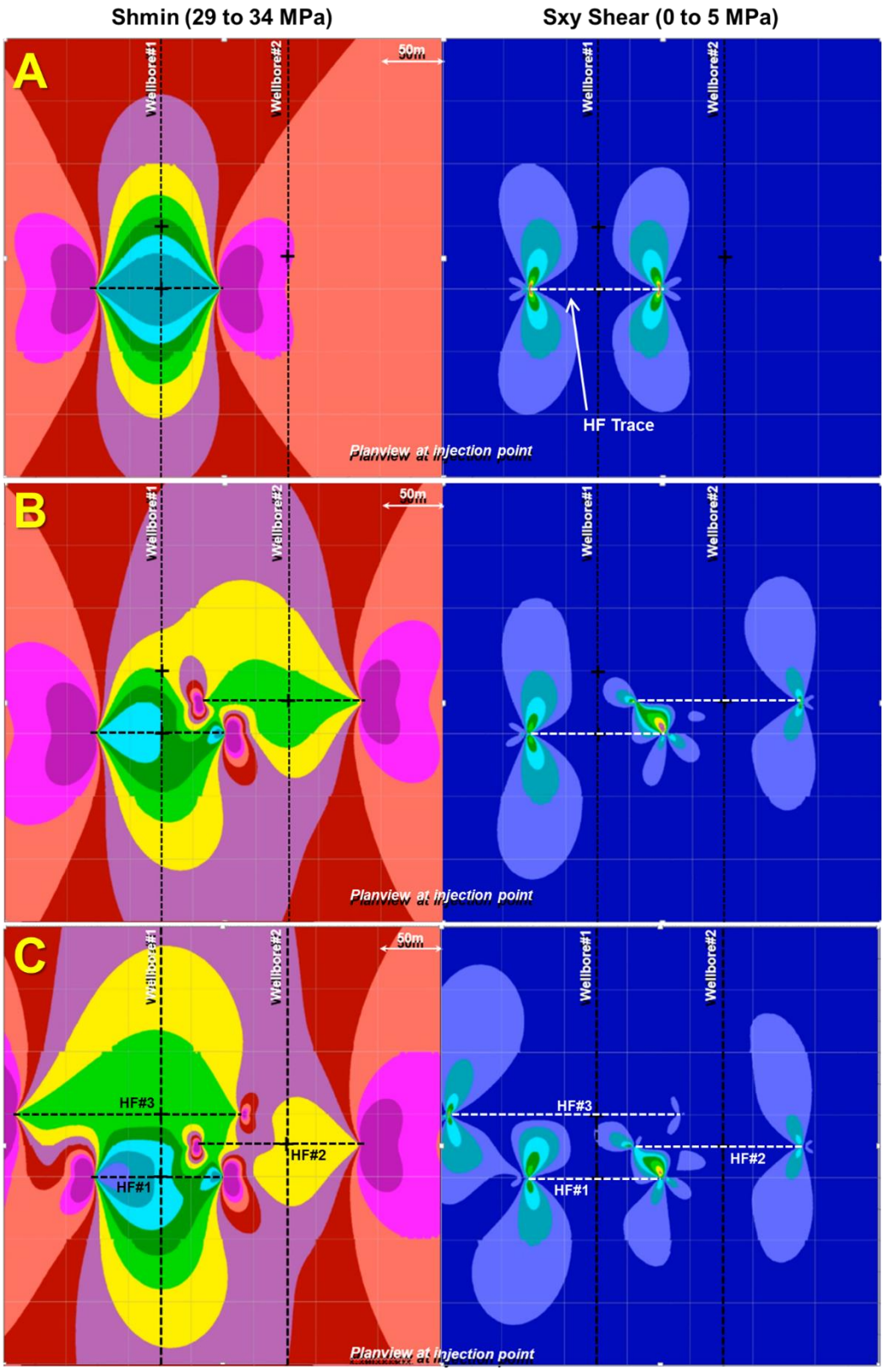

Figure 14: Planview images of the progression in Shmin (left) and tip shear stress (right) for three HFs (top to bottom) in a Zipper Frac configuration.

The critical learnings about Stress Shadows is that: 1) multi-stage and multi-well completions can have significant impacts on the change in Shmin as well as the change in tip shear stress; 2) the impacts include non-symmetric HF growth (both vertically and laterally) and HF lengthening; and 3) the impact on tip shear when HFs overlap, particularly in the region between parallel wellbores, is a tendency to significantly reduce the tip shear.

Stress Shadows and Multi-Cluster-Per-Stage Completions

While the reported industry statistics for the success of multi-cluster-per-stage completions is fairly dismal (the common statistic is that only 40% of clusters contribute to production), the economic reality is that it is not possible to individually stimulate 100 to 200 entry points (or more) from a single horizontal wellbore. One reason that cluster production statistics are so poor is due to Stress Shadows.

Figure 15 shows HF growth in planview from four clusters for a given HF stage. The HF traces are in red and, from plot A to C, grow as a function of injection time. The rate per cluster is the same, which forces an equal volume of fluid into each created HF.

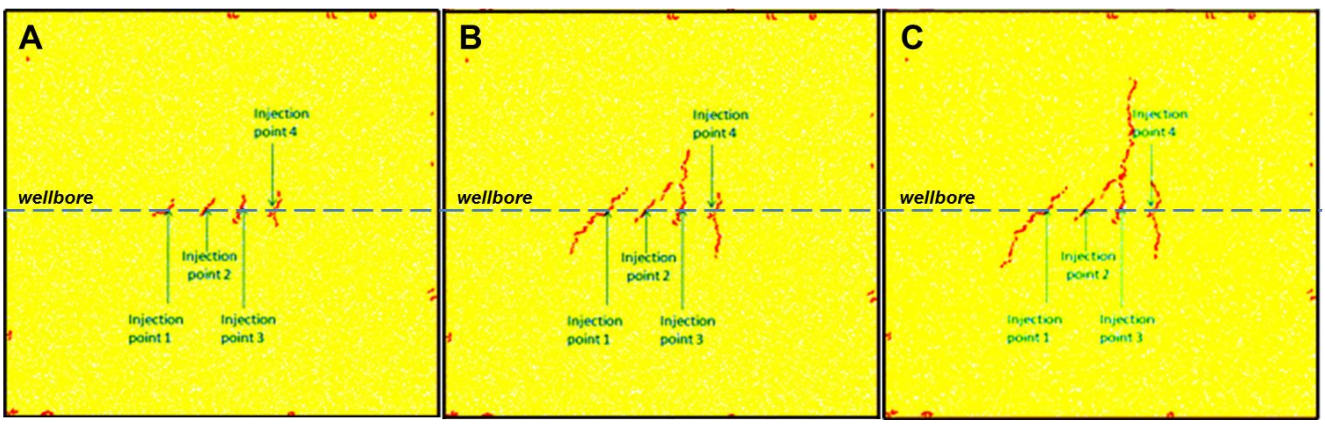

Figure 15: Four-cluster HF growth from a single HF stage as a function of time (A to C).

Due to local heterogeneity (which could, for example, be rock fabric or perf issues or the like), plot A shows a bit complicated early HF propagation. As injection continues, plot B, the two center HFs are dominantly growing towards the top of the figure while the outer two HFs show some upwards growth but dominantly more downward growth. Finally, plot C shows that the two center HFs have grown upwards (and combined) with no downwards growth while the outer HFs have grown dominantly downwards. This behavior is not unexpected and is attributed to Stress Shadows (the increase in Shmin) from the HFs.

When each cluster takes the same fluid volume, HFs from each cluster must be created. In this case, one of the HFs will tend to grow a little bit more than the others (randomly related to local effects making it easier for that HF to propagate that little extra). When this happens, the extra Stress Shadow from this preferential HF impedes the propagation of the other HFs. For the case in Figure 15, as the center HFs grew upwards (randomly), the Stress Shadows from these discouraged upward growth of the outside HFs, which instead grew downwards as this was the path of least resistance.

Unfortunately, unless designed for, each cluster is unlikely to take an equal amount of fluid as the fluid will go into the cluster that is easiest. As a result, one cluster will tend to dominate. This effect is shown

in the left image of Figure 16. In order to offset this effect, limited entry perforation design is used (as shown in the right image of Figure 16).

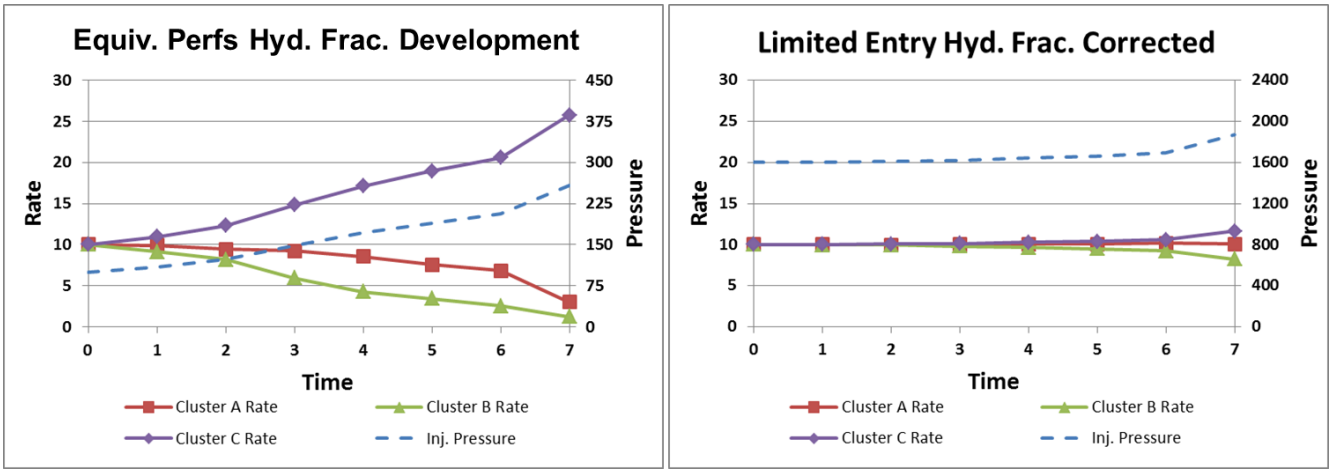

Figure 16: Rate and pressure summaries for equivalent clusters (left) and limited entry clusters (right).

As shown in Figure 16, a three-cluster configuration is considered. For whatever reason, cluster C begins to dominate in the formation in the left plot (the perf clusters are considered to be completely identical) and, as the Stress Shadow (again, the increase in Shmin) grows from cluster C, clusters A and B suffer and less and less rate goes into these clusters. In contrast, the large friction pressure due to the limited entry perforation design in the right plot forces nearly equal rate into each of the three clusters. However, limited entry designs only address the pressure drop across the perforations but do not account for the pressure losses within the perforation tunnel and/or near-wellbore area and, consequently, the use of limited entry has not significantly improved cluster efficiencies.

Figure 17 shows further examples of the influence of Stress Shadows for cases without limited entry (LE) as well as with limited entry. Shown are HF developments for three and four clusters.

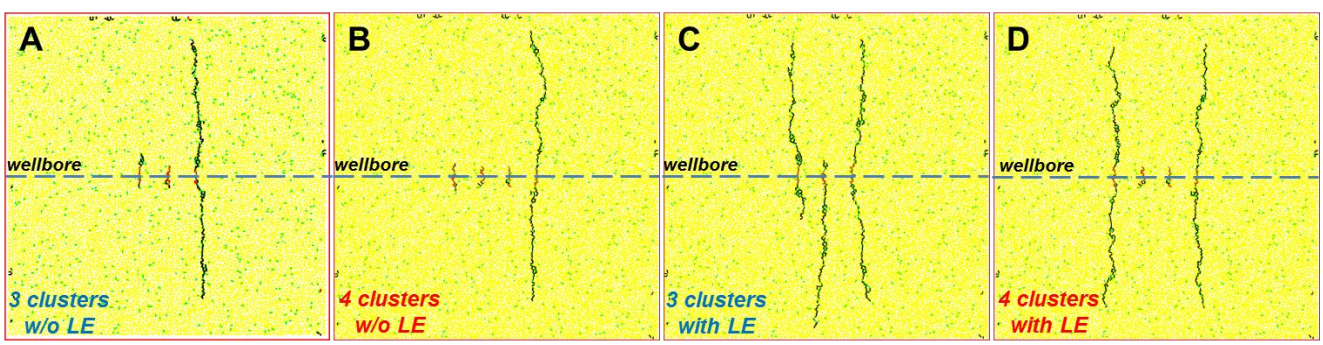

Figure 17: Simulated HF growth for 3- and 4-cluster stages with and without limited entry design.

Plots A and B in Figure 17 show HF developments without limited entry. Whether with three or four clusters, one HF begins to dominate and, due to the increase in Shmin, HF development from the other clusters is completely prevented. In plots C and D, the effects of limited entry are included. In plot C, HFs develop from all three clusters; however, due to the increase in Shmin, the left HF grows upward while the center HF grows downwards. The far right HF in plot C grows equally up and down, but does appear to grow away from the other HFs (due to Stress Shadows). In plot D, diversion at the wellbore

creates two full-length HFs from the outer clusters, but Stress Shadows impede the growth of HFs from the inner two clusters.

The critical learnings about Stress Shadows is that: 1) multiple, closely-spaced HFs will affect the propagation of each other and, often, one will dominate; 2) limited entry cluster design is intended to make the pressure drop at the perforations the primary source of flow dominance/flow diversion (instead of the Stress Shadows from a dominant HF); and 3) even with the best limited entry design, other flow diversion effects (including Stress Shadows) may dominate resulting in only fair or poor cluster flow efficiencies.

Summary and Final Comments

In summary, the concept of Stress Shadows (SSs) may explained as:

- SSs are first, and foremost, a real and understandable effect caused by the deformation of the formation during hydraulic fracturing operations;
- Just as the deformation of the hydraulic fracture is dynamic, so too is the created SS. As the deformation of the HF changes as it closes on proppant, the SS changes. And, to the extent that the deformation of the HF further changes with production (due, for example, to proppant embedment), the SS will also change;
- While the dominant effect of SSs is the increase in Shmin behind the HF tip, the other principal stresses can change and the significant shear stresses generated along the HF tip should also be considered; and
- Because SSs change the in-situ stress field, and because hydraulic fracturing is a path-of-least-resistance-type process largely controlled by the stress field, the changes in the stress field due to SSs should be considered on the development and propagation of subsequent HFs.

See all the articles in the OFG "Geomechanics for Unconventionals Series":

I. *"ge-o-me-chan-ics, A Better Explanation"*
II. *"Geomechanics And Unconventionals: A Match Made in Heaven – or Just (Occasional) Friends"*
III. *"Hydraulic Fracturing: Of Magic and Engineering"*
IV. *"The 'Complexity' Paradigm: Shifting Our Understanding in Order to Optimize Completions in Unconventionals"*
V. *"Stress Shadows Explained: What It Is, What It Isn't, And Why You Should Care"*
VI. *"Why 100 Mesh in Unconventionals"*
VII. *"On the Geomechanics of Zipper Fracs"*
VIII. *"Who Redefined Frac Gradient: And Why?"*
IX. *"Completion Engineer for a Day"*
X. *"On The Geomechanics of Refracturing"*
XI. *"Sand Volume per Unit of Lateral Length: Is There a Geomechanical Justification?"*
XII. *"It's the Rock Fabric, Stupid!"*