Subsurface-Driven Completion and Well-Design Changes to Maximize Value in the Marcellus*

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Abstract

A fundamental conundrum common to Unconventional plays is how to understand the relative contribution of the subsurface versus the drilling and completion practice to Estimated Ultimate Recovery (EUR), given the inter-connectedness of many parameters. It seems plausible that the completion- or well- design should change where there is a significant change in the subsurface. In reality however, this is difficult to implement because intuitive solutions to optimize the interaction of the wellbore with the sub-surface are often hindered by a requirement for quantitative and statistically valid proof, typically measured in the increase in a production performance metric, like EUR. To address these technical and cross-discipline integration challenges, a new structured workflow was derived using data from the Marcellus Shale in Tioga County, Pennsylvania, including production from 230 wells. This workflow produces a framework that provides confidence in a value-based assessment, for both engineering-design changes and development decisions. Most steps in the workflow are applicable to all Unconventionals, but the confidence level increases with more wells.

Ways to Understand EUR

Understanding the drivers for maximizing EUR in Unconventionals is not straightforward and becomes more complicated when there is a lot of subsurface heterogeneity in a play, or when wells are not comparable, for example due to variable lateral lengths or a completion design change. Ultimately, to understand EUR, one has to compare more than one well. Some ways to do this are listed in Figure 1.

Attempts to search for correlations between EUR and a single parameter (method 2), be it subsurface or engineering, were not fruitful, typically yielding low correlation coefficients (R^2). More crucially, such crossplots can provide "false negatives", potentially eroding significant value. Awareness of cognitive biases prompted a multifaceted approach (method 7) applied in a rigorous and structured workflow.

Workflow: Hypothesis-Based Development

Also using layers, the *Hypothesis-Based Development* workflow is complimentary to the commonly applied *Play-Based Exploration*, but includes methods for handling production data. It is best described as a structured workflow for carrying out a review of the drivers for well performance across an asset, both subsurface and engineering, integrating multiple techniques (Figure 2). Although 230 wells were used in this case study of the Marcellus, this workflow has also been successfully applied in an area with ~10 wells, albeit with greater uncertainty in results.

Whether 200 or 2 wells, if the goal is to compare EURs (or IP90s) to understand the drivers, then some degree of normalization is required. In the Marcellus, lateral length and pressure were accounted for using an inverse productivity index (1/m). An attempt was made to normalize for the subsurface by using the equation for Gas-Initially-In-Place (GIIP), in which gross thickness was the only parameter that could be mapped with high confidence, and was conveniently bucketed into 25 ft isochores.

Hypotheses to explain well performance from both an engineering and subsurface origin were formulated. Each hypothesis was based on physical processes. It is important not to discard hypotheses at this stage, even if belief in them is not strong.

In order to high-grade the hypotheses, a novel technique was invented - *Outlier Analysis*, in which the very best and very worst wells (normalized by 1/m and lateral length) were scrutinized in each thickness region (isochore polygon) – i.e. the outliers in performance. Each well was assessed against each hypothesis and results collated to spot trends in groups of wells. Underlying this technique is an assumption that the best chance of understanding the relative contribution of the subsurface versus the engineering comes from an investigation of end-members in the range of performance, in which a specific interaction between the rock, wellbore and the stimulation may have been make or break factor. The next steps in the workflow (described below) are to create a *Framework Map*, validate it with modeling and competitor data, followed by implementation of an engineering-design change, or a field development change.

Structural Hypotheses

The value of hypotheses is illustrated by attempts to understand the impact of structural complexity across the Marcellus acreage. An initial assumption, driven by an experience base of conventional fractured reservoirs, was that natural fractures help EUR. Development of a structural architecture (Figure 3) based on detachment folding and large-scale kink-bands (Gillespie et al., 2015) allowed the formulation of other hypotheses, such as “higher bedding dips impede fracture height” and “discrete kink-band axial planes steal frac fluid and prevent stimulation of surrounding shale” (Stephenson et al., 2013). Crucially, the physical process for the interaction of the hydraulic stimulation with each structural feature was identified and the corresponding hypotheses were quantified to allow them to be mapped out.

Technical support for the hypotheses was also sought from data and trials. For example, microseismic was collected across a kink-band in the hinge of a detachment fold, in an area also cross-cut by a NNE-SSW trending strike-slip fault (Figure 4). It was observed that hydraulic half-length of the stimulation was impeded by the vertically-pervasive strike-slip fault, with fluid diverted into the fault plane. Furthermore, the hydraulic fracture height in the kink-band was severely limited; interpreted to be a result of bedding-parallel slip-surfaces (with striae) causing weakened bedding interfaces; the stimulation (or reactivation) of which is facilitated by the higher bedding angle within these domains.

The following hypotheses were formulated with respect to the folds:

- Bedding dips greater than 5° impede fracture height and hinder EUR.
- Kink-band axial planes parallel to *in situ* stress steal fracture fluid and hinder EUR.
- Natural fractures on fold crests enable a stimulated rock volume (SRV) and enhance production.

Scrutiny of these hypotheses against the normalized production performance data-set using *Outlier Analysis*, confirmed the first two hypotheses, but found no evidence for the third. It does not necessarily follow that the natural fractures in the Marcellus are having no impact on the stimulation, but more probably that the impact is not measurable relative to other subsurface heterogeneity, such as domains of higher dip, strike-slip faults or changes in stratigraphic layering.

Focusing on hypotheses helped elucidate that every aspect of the subsurface need not be characterized in order to understand production. For example, if the variability in natural fracture intensity within the Marcellus Shale is small, then the corresponding variability in production would be anticipated to be also small. The same argument holds true for porosity. Porosity is important for assessing reserves, but the variability in porosity across the acreage, as with natural fractures, is probably not a key driver for the optimization of the completion and stimulation design.

A Production-Constrained *Framework Map*

Hypotheses with support from trends in production data were mapped out in *Petrel* to produce a *Framework Map* (Figure 5). It proved useful to differentiate between hypotheses related to the GIIP and those related to the *access* to that GIIP. Both groups of parameters drive production performance, but we only have control over the second group. It is worth re-iterating that the Framework Map is not a traditional subsurface map, but a compilation of key subsurface drivers as layers, constrained by those hypotheses with support from production data.

The Marcellus framework map has a fit with >80% of 230 wells. In other words, a well that lies within an area with an *access-to-GIIP* constraint has an 80% chance of having an EUR lower than that derived from the type curve. This is a much higher level of predictability than correlation with any single parameter and was the key result to provide confidence in the map. Because most of the sub-surface heterogeneity constrains well performance in some way, the acreage was divided into *Constrained* and *Unconstrained*; a useful concept to communicate the potential of an upcoming pad. For example, drilling-unit A is in an unconstrained area, whereas drilling-unit B is partly constrained by rock with high bedding dips (Figure 5).

To challenge and further validate the result, the Framework Map was tested in multiple ways through dynamic modeling incorporating key subsurface drivers to understand the expected EUR range associated with those drivers.

Probably the most convincing proof of the Framework Map ultimately came from a regrouping of the wells (Figure 8). Using isochores and the constrained versus unconstrained sub-division, the range in EUR decreased substantially, compared to previous groupings based on close proximity (i.e. geography). Moreover, there was clear separation between the constrained and unconstrained well groups. This result had many ramifications from a reserves re-assessment to drilling schedule changes.

Subsurface Driven Engineering Design Changes

Despite multiple completion optimization trials, the primary control on production performance was concluded to be the subsurface variability, and to address this, six drilling and completion design changes were recommended to maximize the value of highly heterogeneous acreage (Figure 9). Each of these recommendations is substantiated by an increase in value, not just EUR. In addition, each well has some general criteria to honor: to stay toe-up, without causing undulations; to stay in zone; and to avoid hydraulic fracturing seismically visible breaks parallel to the maximum horizontal stress ($\sigma_{Hmax.}$).

Conclusions

- The rock is the main control on EUR (estimate 75% subsurface and 25% Engineering).
- The *sweet-spot* is not just a function of the resource density (GIIP), but also the access to that GIIP.
- *Hypothesis Based Development* is a workflow to test hypotheses, accurately assess completions trials, properly gauge competitor performance and develop map-based development strategies.
- The *Framework Map* represents the key subsurface variability related to GIIP and *access-to-GIIP*, for which there are supporting trends from production data.
- >80% of wells fit the Marcellus Framework Map to some degree.
- One well design will not create the maximum value for the asset.
- One completion and stimulation design will not create the maximum value for the asset.
- It is not productive to do a completions optimization trial for enhanced EUR in poor rock.

References Cited

Gillespie, P., J. van Hagen, S. Wessels, and D. Lynch, 2015, Hierarchical kink band development in the Appalachian décollement sheet: AAPG Bulletin, v. 99/1, p. 51-76.

Stephenson, B., R. Fannin, C. Dick, M. Williams, and D. Cakici, 2013, Structural stage spacing: a win-win-win technique for costs, EUR and HSE: URTeC Conference, Denver, p. 8, No. 1577021, SPE 168718.

1. Statistical

Assume the variability is being captured and have enough data-points to define a distribution.

2. Search for correlations with sub-surface or engineering parameters.

Cross-plot individual parameters (univariate analysis) or multi-variate analysis.

3. Normalize for geology to understand completions effectiveness.

Compare wells in geologically similar areas, or find a methodology to minimize the geological variability.

4. Normalize for the completion & stimulation to understand the sub-surface deliverability.

Calculate a way of capturing engineering aspects of a completion, e.g. dividing EUR by # fracs.

5. Use analogue wells

Compare well results between operators and try to understand the differences.

6. Modeling

History matching and/or forward modeling, typically using data from trials as constraints.

7. A combination of the above.

In the absence of obvious levers, a multi-faceted approach can increase confidence in decision making and reduce cognitive biases.

Figure 1. Possible methods to compare wells to understand EUR.

- **Normalize** flow **for the well-bore**: use inverse productivity index (1/m) for pressure and also account for lateral length.
- **Normalize for the sub-surface**: gross thickness (isochores) was used as a proxy for HCIIP.
- Brainstorm **hypotheses** that might affect EUR: Use sub-surface, drilling & completions and flowback categories and then consolidate.
- Scrutinize the very best and very worst wells (from 1/m) in each isochore to high-grade the hypotheses (called **Outlier Analysis**).
- Create a **Framework Map**: map out those hypotheses that are supported by Outlier Analysis, and distinguish between changes relating to HCIIP and access-to-HCIIP.
- Use **dynamic modeling** as a sensitivity analysis to quantify potential production changes related to individual sub-surface or completion parameters.
- Use **multi-variate analysis** as an independent cross-check of those hypotheses that are supported and assess the relative impact in the HCIIP and access-to-HCIIP parameters with tornado charts.
- Create **scenario maps** to enable development and economic decision-making.

Figure 2. Steps in the Hypothesis-Based development workflow.

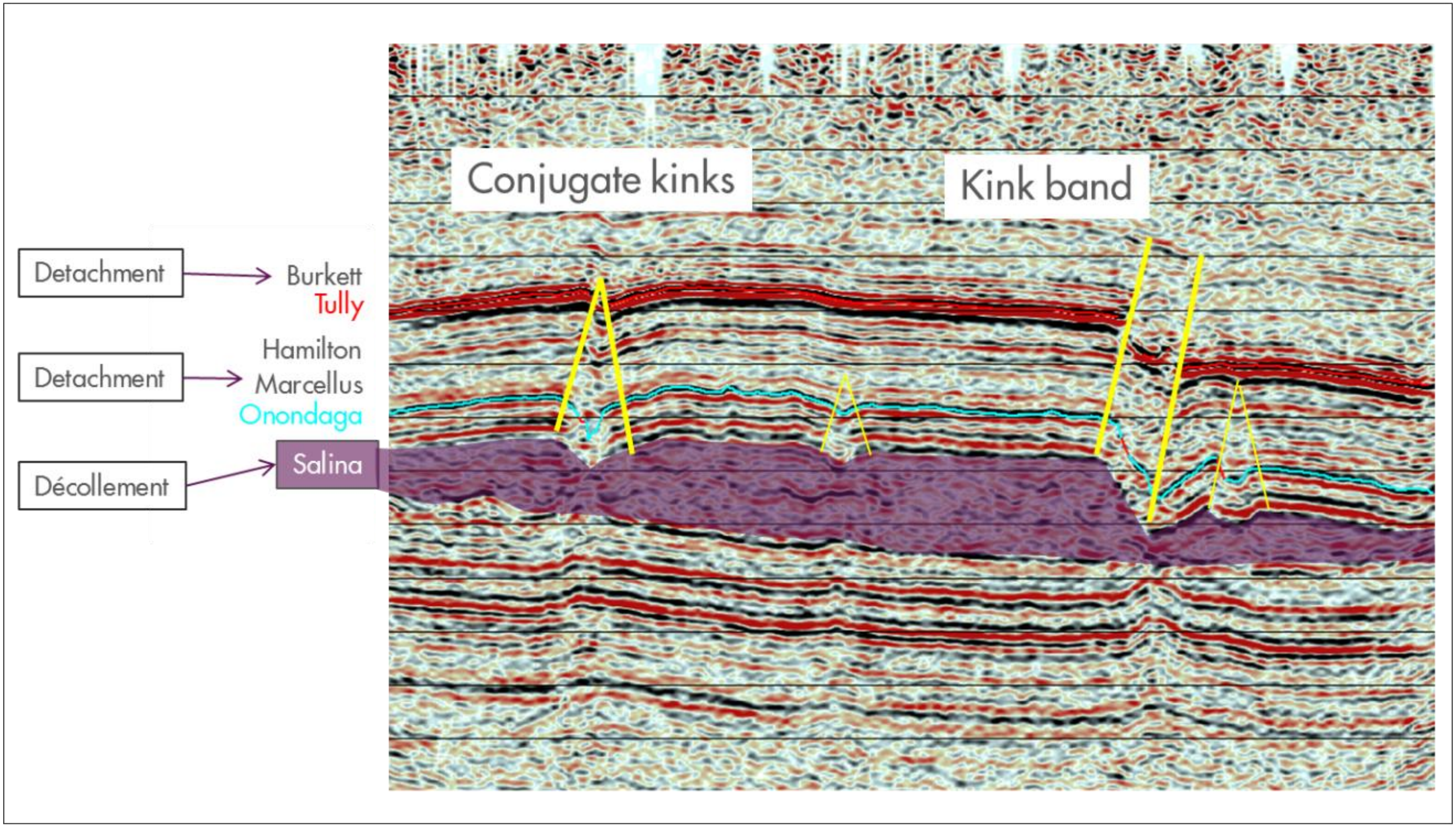

Figure 3. Structural elements of the Marcellus play.

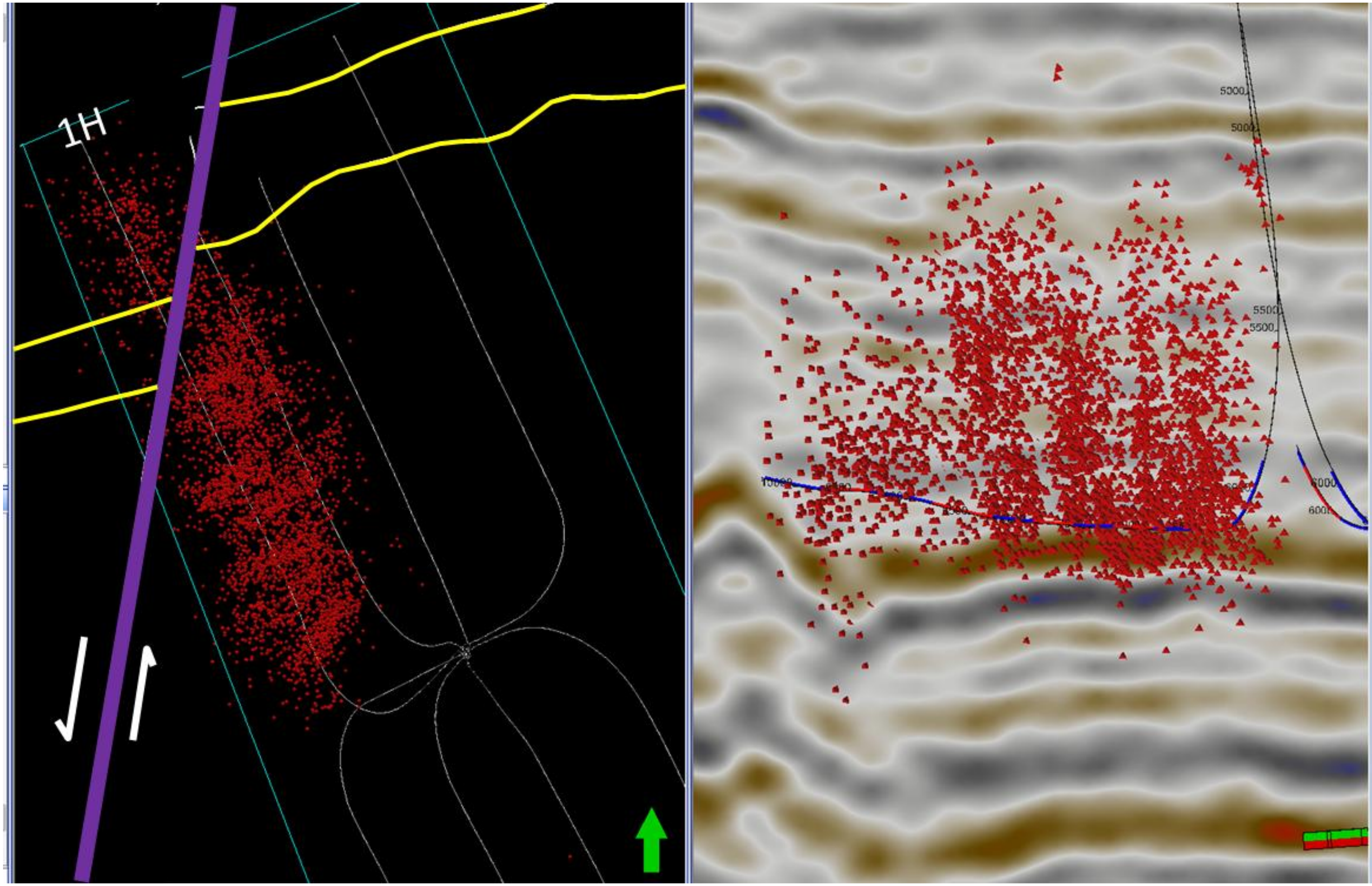

Figure 4. Microseismic across a kink-band (yellow lines) and strike-slip fault (purple line) in the Marcellus.

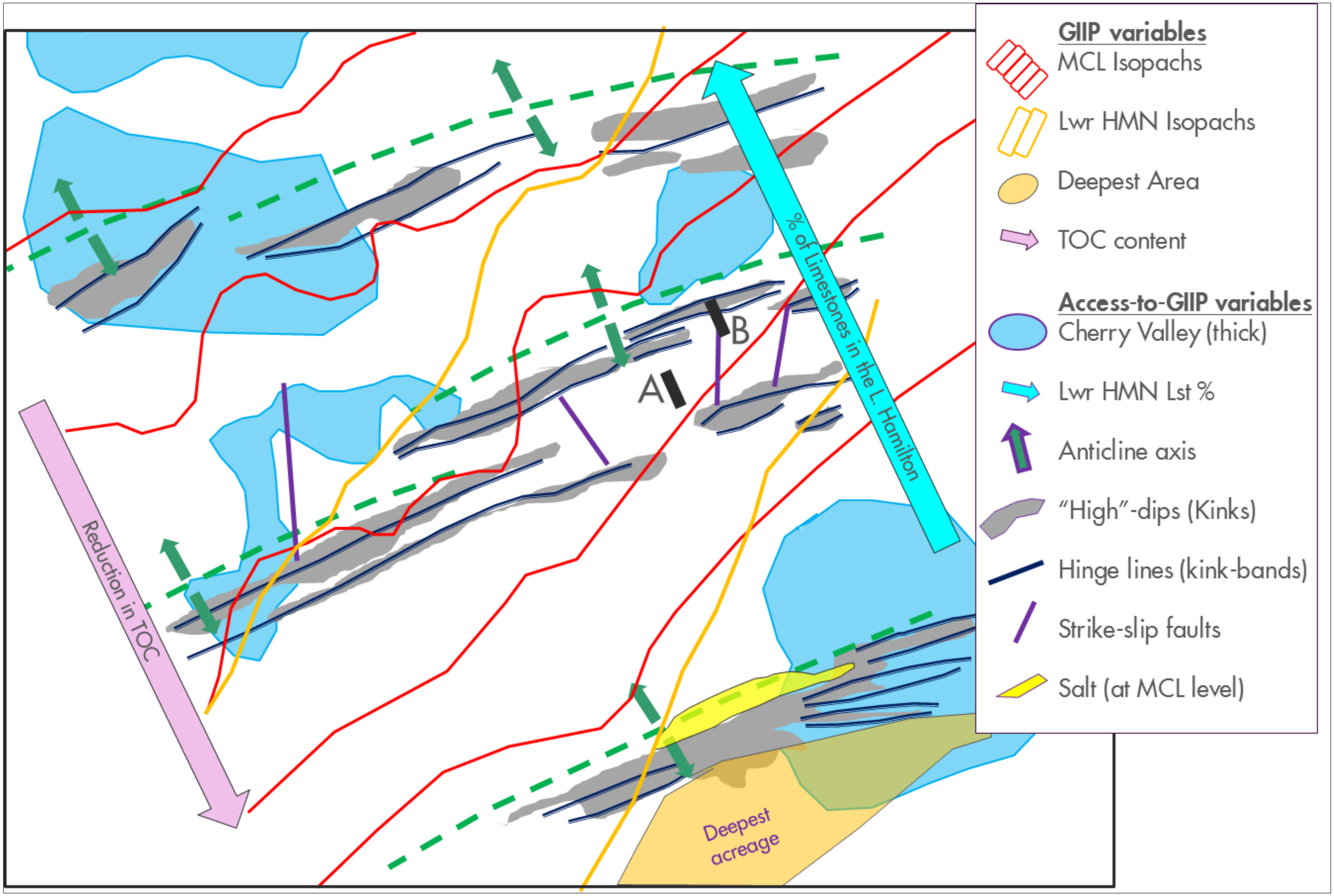

Figure 5. Framework Map for the Marcellus, comprised of production-validated hypotheses.

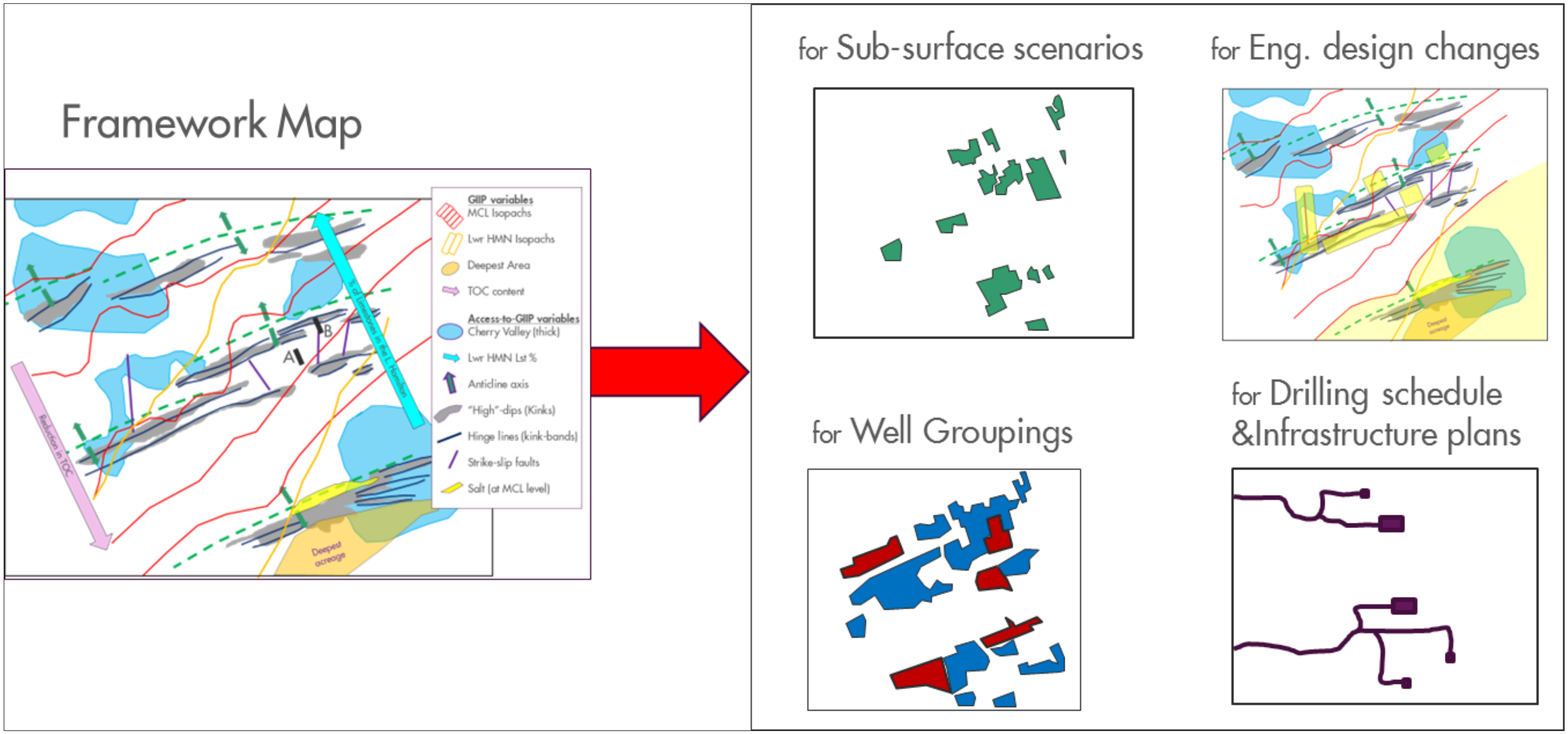

Figure 6. How the Framework Map was utilized to implement change.

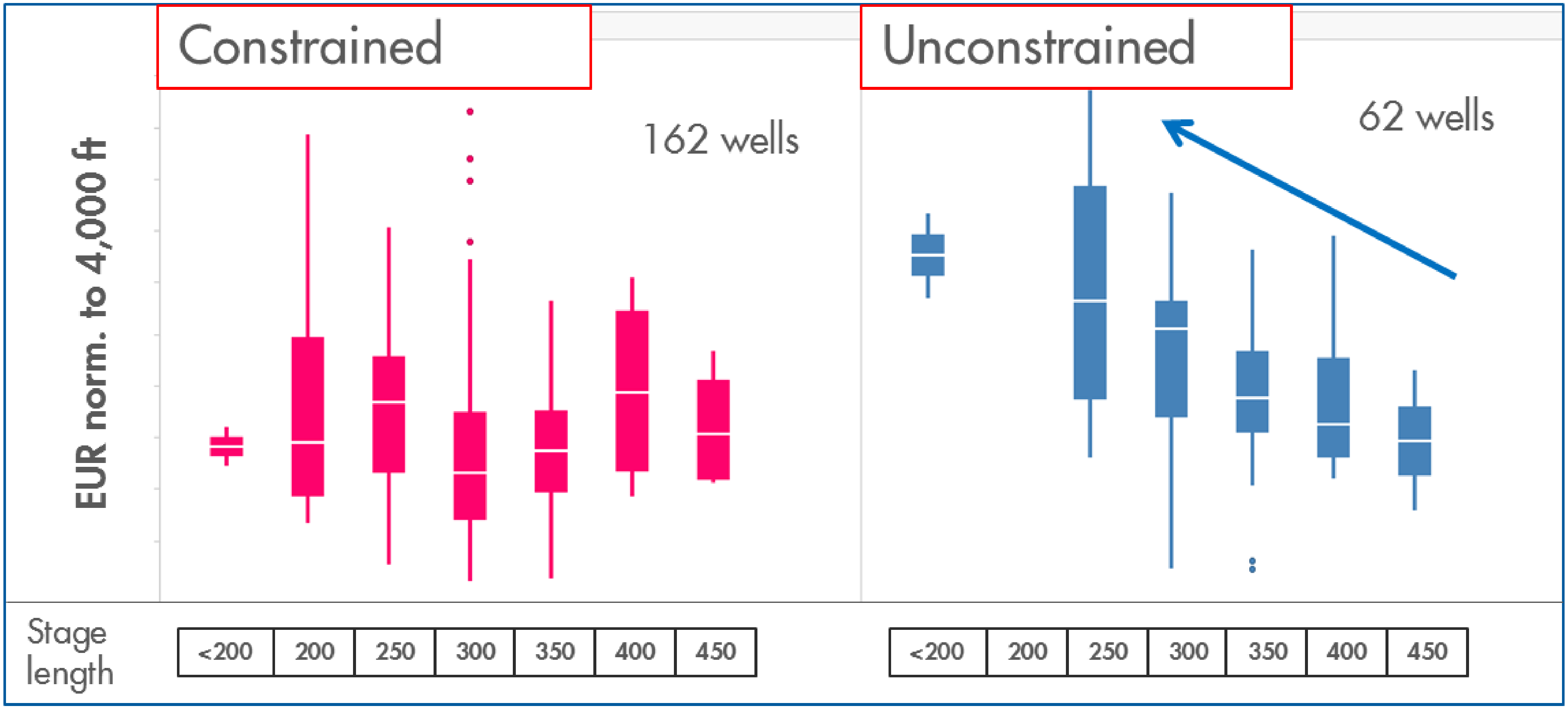

Figure 7. A comparison between normalized EUR and stage spacing for constrained (left), and unconstrained acreage (right).

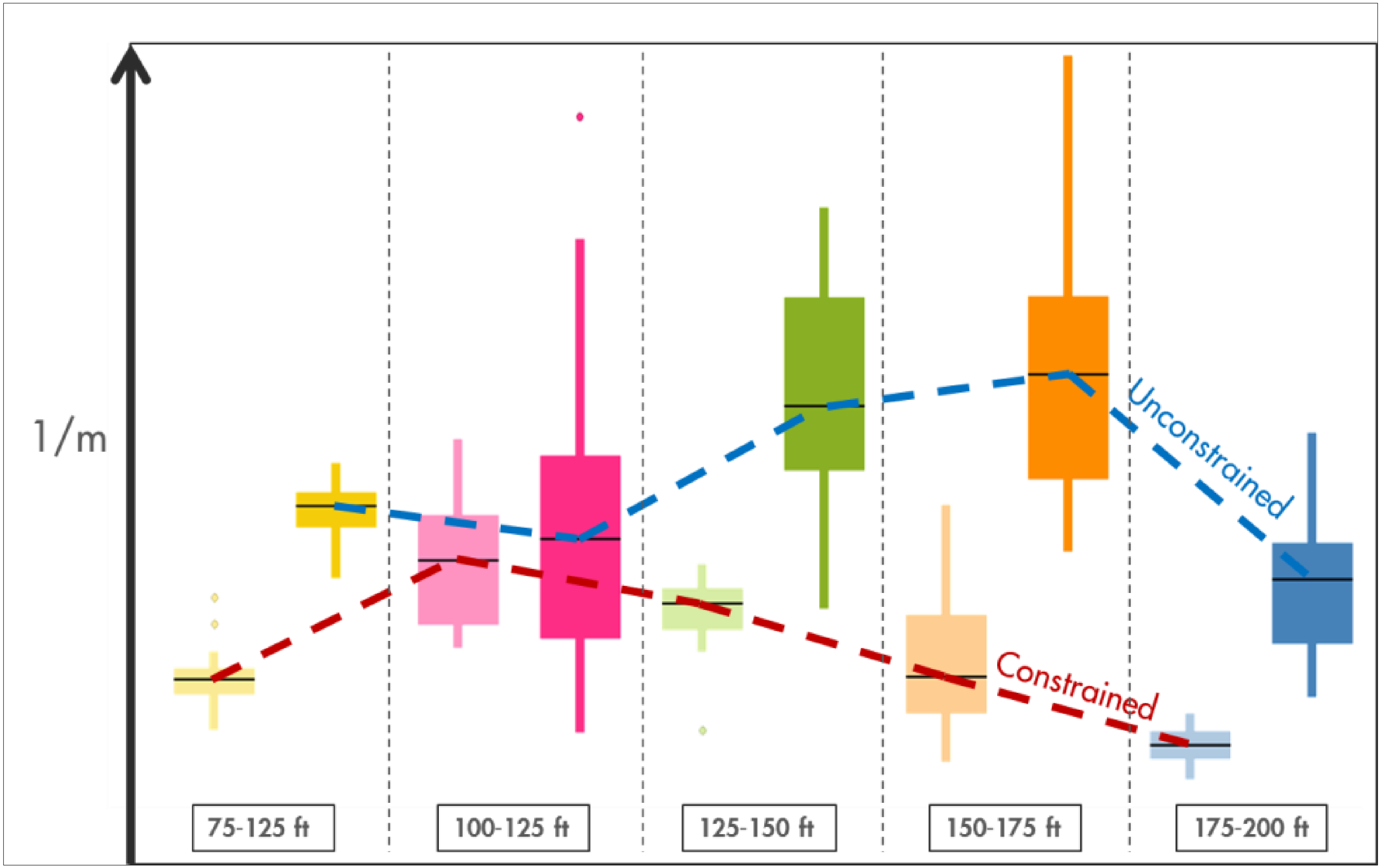

Figure 8. Ranges of inverse productivity index (1/m) for wells in different isochores, differentiated between constrained and unconstrained acreage.

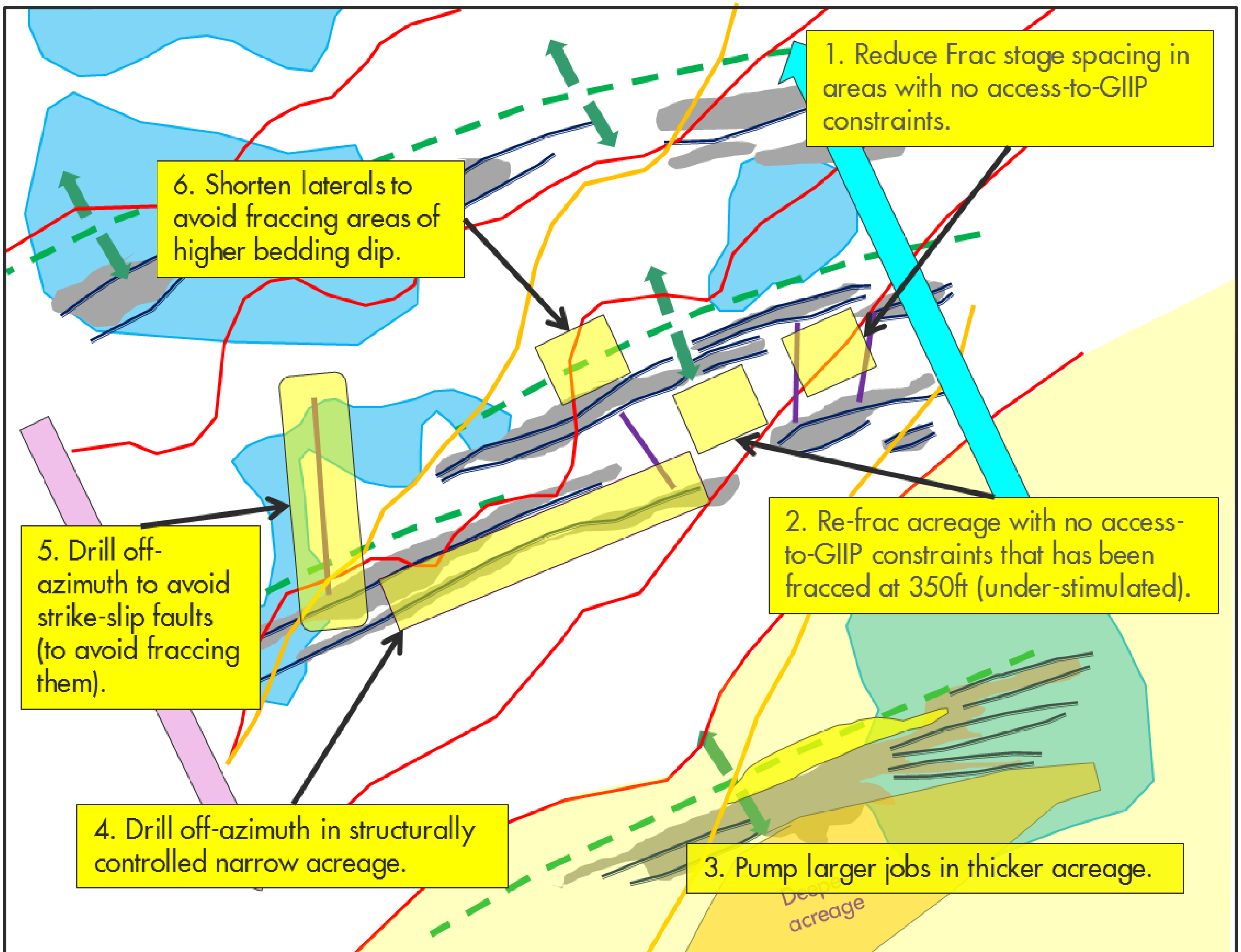

Figure 9. Recommended well engineering, completion, and stimulation design changes for the Marcellus, derived from the Framework Map.