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Managing Drilling Losses in the Permian Using Airborne Gravity Full Tensor Gradiometry

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Abstract

Shallow drilling losses are a significant problem in the Permian basin because of the presence of subsurface karst features. Karst weakens the soluble rock producing voids and caves systems that result in drilling losses. An operator drilling in Culberson County, Texas recently experienced total losses drilling four surface holes in a pair of neighboring pads located in bordering leases. Drilling into caves negatively affected operations by reducing the drilled footage per day, increasing fluid and cementing costs, and increasing the difficulty in performing satisfactory cementing jobs to cover the water table.

This paper will describe the issues faced drilling with losses and explain how to manage the risk of losses by improving surface well placement with airborne gravity full tensor gradiometry (FTG) to map subsurface hazards.

Airborne gravity FTG measures the directional components of the gravity field. Multiple simultaneously acquired tensor components allow identification of anomalies associated with subsurface voids. For this project, a Basler BT67 aircraft acquired data over the targeted expanse with line spacing of 328 ft. The aerial survey took place over 3 days in July 2017.

Feasibility modeling using Castile formation cave systems reveals detectability of single caves larger than 10 m diameter with FTG, however networks of smaller caves are also detectable. Polygons created from analysis of negative vertical gravity tensor (Tzz) anomalies separate the cave systems into tiered risk areas.

Initial analysis reveals risk at both pads where losses occurred. Extending the analysis to the entire survey, the drilling events in the drilled offset wells match with the risk interpreted for karst. FTG data and subsequent interpretation offer strong correlation to known shallow hazards and cave systems, making it a useful tool for risk assessment. It recommended to locate future drill pads in the identified moderate risk areas and that any new wells be located away from elevated risk areas.

This is the first application of FTG to classify drilling risk of karst features in the Permian basin. The FTG hazard map improves operational integrity of surface location selection and is a complement to surface topography and geology considerations. The FTG data and analysis also holds promise for fault mapping and for water drilling efforts.

Introduction

In 2016 an Operator contracted a service company to drill a series of wells in the Permian. The goal of the project was to drill three casing string development wells targeting the Wolfcamp formation. Some of the pads on the project drilled using a lumpsum turnkey contract model.

The first pads, Pad A and B located about 2,000 ft from each other, consisted of four wells located in the northeastern corner of Culberson county, Texas. Thirty-three feet separates each 20-in. conductor, set to 105 ft measured depth (MD), with alignment of the pads in the South/North direction. The well design consisted of a 14 3/4-in. surface hole drilled to 2,350 ft MD to set 11 3/4-in. casing inside anhydrite. State regulators approved a dispensation to deep set this surface casing, rather than immediately set it after drilling past the shallow water aquifer, known as the Rustler, located at a depth of 325 ft MD. The use of a diverter system mitigated the risk of shallow gas known to occur in the region.

Karst features are common in the outcropping Castile formation (Stafford 2013), immediately west of the well pad site. These features include open caves, sinkholes and collapse breccias in varying stages which have formed in the extensively dissolved Castile, Salado, and Rustler formations. Initial speleogenesis is thought to develop along fracture or fault planes, where solution waters may percolate further into the soluble host rock. Surface karst indicators may be obscured by more recently deposited aeolian or alluvial sediments. Drilling losses may occur deeper in the Permian basin due to high mud weights needed to manage pressure through injection zones (Thibodeaux et al. 2018). Detailed offset well information provided by the Operator, including daily drilling reports and mud logging data, on twelve wells drilled from 2013 through 2015, showed no risk of losses in surface hole section.

Four of the eight wells on the first two pads drilled with mud returns and without issue. Reduced drilling parameters limited wash around the conductor until all drill collars were out of casing. Minimal washout in the salt zone occurred by swapping native fresh water to brine around 1,500 ft MD. Circulating the casing at total depth was uneventful and pumping the cement jobs resulted in an excess of cement on surface. No shallow gas was observed.

Total losses occurred on the other four out of eight surface sections. The northernmost well on Pad A and the three northernmost wells on Pad B experienced losses negatively impacting drilling operations. In each case losses that occurred progressed into total losses while drilling. Rojas et al. (1998) and Wang et al. (2005) describe techniques to limit drilling losses. Drilling blind is risky because of the increase on project logistics and potential to lose the wellbore. Mud, lost circulation material (LCM), and mud trucking costs increase to keep up with the losses. Waiting on mud can occur given the distance from water sources and high drilling activity in the basin. Decreasing the drilling flow rate increases the risk of stuck pipe unless the rate of penetration (ROP) is reduced to account for the reduction in hole cleaning. Once losses occur it is difficult to evaluate the adequacy of the hole cleaning regime. If the fluid level in the wellbore drops then the well might kick, dangerous considering the risk shallow surface gas, or the wellbore might collapse.

Cementing is problematic because it is difficult to estimate the depth range and radial extent of the loss zone. Maskary et al. (2014) describe the main considerations for curing losses while drilling and cementing. A caliper log from wireline helps to characterize the extent of the losses zones and determine if they are caves. It is critical to circulate cement to surface to isolate the shallow aquifer before drilling the intermediate section, otherwise a top job or costly remediation are required. Extra materials and services to combat losses increasing total well cost. Finally, drilling into caves slows down the time to get the well producing.

Mitigating the Losses While Drilling

The first well that experienced losses, Well 1 on Pad A, lost fluid returns at 537 ft MD. An LCM mix with a wide particle size distribution, pumped at 33 to 44 lbm/bbl, did not lessen the losses. The fluid level kept a surface while drilling. The wireline caliper log showed 16 – 18-in. wash to 325 ft MD and from 325 to 500 ft MD the caliper arms maxed out to 28-in. A stage tool was used to pump multiple cement jobs above the loss zone. The first cement job through the stage tool consisted of 236 bbl of 14.8 lbm/gal cement resulting in 40 – 50% returns circulating after waiting on cement. An extra 177 bbl of 14.8 lbm/gal cement was pumped with LCM material resulting in 50 bbl of cement back to surface. The cement bond log (CBL) showed a satisfactory cement job. Two more surface sections drilled in batch did not experience losses. The extensive time used to mitigate losses on the first well of the batch set ended the batch set prematurely after drilling three surface sections instead of four. The fourth surface section, drilled at a later date, did not suffer from losses.

On Pad B Well 2 total losses occurred from 494 ft to section total depth (TD) despite decreasing the drilling flow rate of 850 galUS/min down to 450 galUS/min. Even at this reduced flow rate multiple water trucks worked full-time to continually bring drill fluid to the rig site. Pumping polymer LCM and spotting a heavy LCM pill with a dedicated dumb iron bottom hole assembly over the suspected loss zone from 550 – 400 ft MD had no effect. Losses continued throughout the surface section. After drilling to TD the caliper log showed multiple potential loss zones. Notably there is a cavernous region found from 300 to 600 ft MD, the top third of the surface section. Fig. 1 shows the caliper recorded on Pad A Wells 2 and 4. The extent of the caves is unknown because the caliper arms on the wireline tool maxed out. The hole goes out of gauge first around 288 ft MD and back in gage until section TD around 720 ft MD. The caliper logs suggested caves favoring cement to cure the losses rather than more sophisticated LCM used in wellbore strengthening applications.

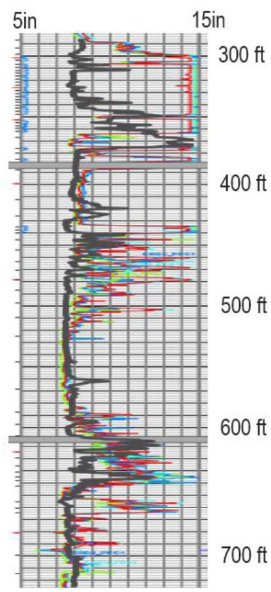

Figure 1—Pad B Well 2 and 3 Caliper Radius Comparison.

Cement can be pumped from a stage tool run in the upper part of the casing. The shallow water aquifer drives the minimum setting depth for the stage tool, in this case below the loss zone. Unfortunately it took four separate second stage cement jobs, totaling 782 bbl of cement, to fill the caves and circulate cement back to surface. The poor condition of cement coverage near surface resulted in a top job to complete the mitigation of losses on Pad B Well 2. Comparatively the typical surface job with 150% average annular excess called for 617 bbl of cement. The poor results using the stage tool drove the drilling team to deal with the losses before running casing on the later wells.

On the next well, Pad B Well 3, losses occurred similarly to Pad B Well 2 despite using conservative drilling parameters to mimic Pad B Well 1, drilled without losses. Partial losses observed from 313 ft MD progressed to total losses by 1,354 ft MD. Drilling parameters when losses occurred were: 450 galUS/min, 2 – 9 kip, 30 – 56 RPM, 400 psi differential pressure, 59 ft/hr average rate of penetration. The mud level remained visible while drilling. Full circulation returned after drilling to TD then setting a 315 bbl balanced cement plug from 800 ft MD to a top of cement at 300 ft MD. The fluid caliper showed 20% washout after the balanced plug, a 50% decrease in washout. Full returns held circulating casing at TD and during the cement job.

On Pad B Well 4 losses began at 375 ft MD and drilling continued to 946 ft MD, past the base of the loss zone. Drilling operations halted to set an intermediate balanced plug across the loss zone with the goal of reducing mud costs for the rest of the section. The 315 bbl balanced plug, set from 800 ft MD to a top of cement at 293 ft MD, did not preserve full circulation as drilling continued. The leading and trailing edges of the cement sheath around the loss zone seemingly wore away because of friction from pipe rotation resulting in partial losses drilling to 1,000 ft MD. Another balanced plug consisting of 426 bbl of cement set from 800 ft MD to 80 ft MD unintentionally sidetracked during drill out. The losses cured with a final open hole cement plug set over the loss zone after drilling to TD in the sidetrack. The final casing cement job took place in two stages, again using a stage tool, because partial losses occurred circulating the casing near TD. Although each surface section with losses eventually circulated cement to surface successfully a satisfactory mitigation plan was elusive. Over 1,900 bbl of extra cement was pumped above the original plan for the Pad B surface batch set.

Impact of Losses

On Pad B the three surface sections drilled with losses needed an extra 15.1 days to finish. Fig. 2 shows the days for each surface section on Pad B and the next pad, Pad C, versus the plan.

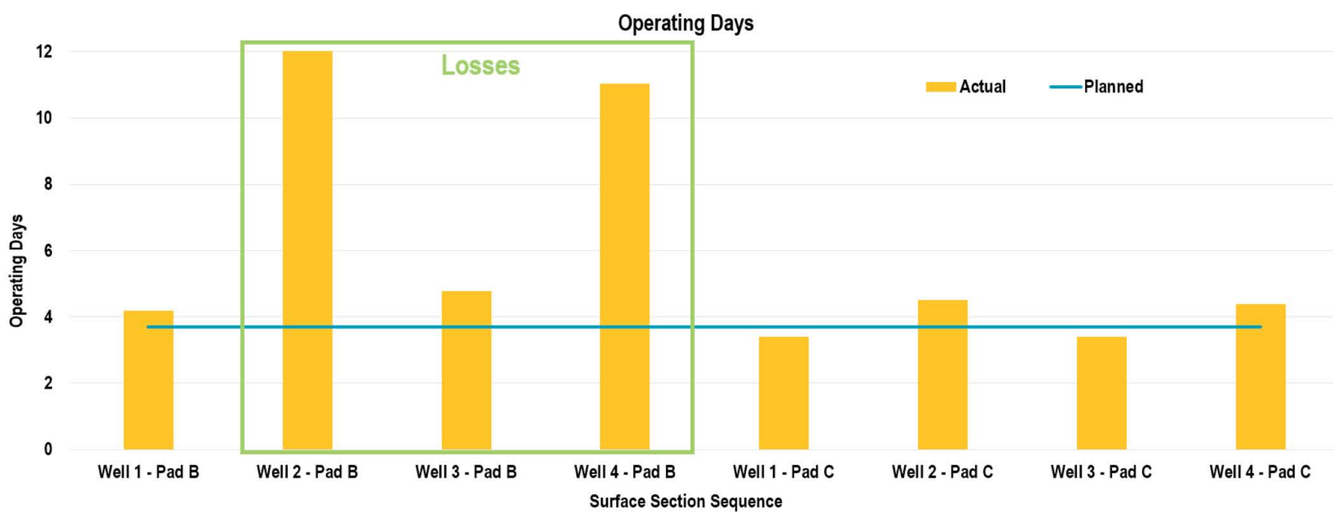

Figure 2—Pad B Surface Batch Set Operating Days vs. Plan.

The Pad B batch set planned to drill all four surface sections in 15 days, however it took 30 days. Fig. 3 show the cost proportions to manage the losses on Pad B.

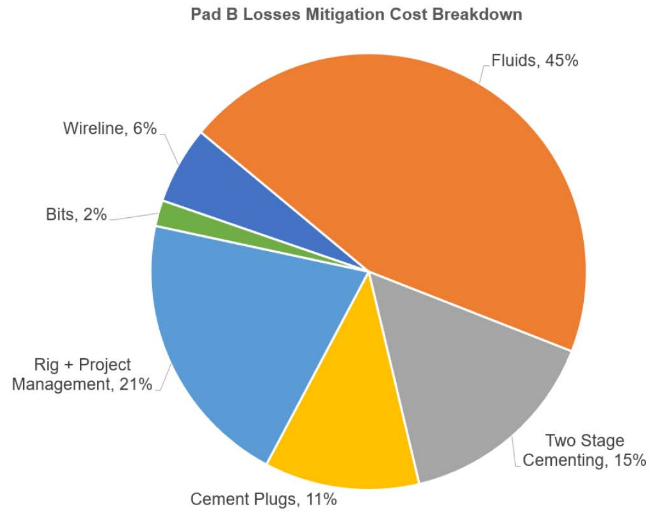

Figure 3—Pad B Cost Breakdown.

Fluid costs were the highest additional cost, reinforcing why balancing the drilling flow rate, fluid reserves, and water trucking logistics were critical to limiting downtime. Rig and project management were then next highest costs because of the time needed to manage the losses. These costs were highest on Pad B Well 2 because of the multiple second stage cementing pumped through the stage tool and on Pad B Well 4 because of the unintentional sidetrack. Additional costs to mitigate the losses include cement plugs, wireline logging for caliper and CBL evaluation, and more bits for clean out runs. Mitigating the losses increased the average cost of a surface hole section threefold.

Given this it was imperative to not drill into caves on the following pad. To achieve this an improved understanding of subsurface geology was needed since drilling into caves was not expected. Internal technical discussion pointed to a potential method to characterize subsurface caves using interpreted airborne full tensor gravity gradiometry.

Aerial Survey & Interpretation

Airborne gravity FTG measures the directional components of variations in acceleration due to gravity. Developed for submarines to detect underwater objects for collision avoidance, the technology became declassified in 1994 (Bell et al. 1997; Cevallos 2015). Multiple simultaneously acquired tensor components allow identification of subsurface anomalies like caves (Coburn et al. 2003). Additionally FTG has been used to define the structure of salt domes (Ennen et al. 2011; Saad 2005). Initial FTG interpretation equates the lowest Tzz to a lone cave. Alignment of Tzz minima is analogous to a cave system. Alternatively the places of Tzz maxima were suspected to be zones least likely for losses or safe zones.

To acquire the data a Basler BT67 airplane flew over the drilled and proposed drilling areas, consisting of about 41 square miles. The BT67 flew at 80 to 100 meters of altitude with line spacing of 328 ft. The flight took place over 3 days in July 2017. The airplane flew the serpentine pattern using terrain hugging topography to keep a constant altitude. The acquired Tzz is then filtered and mapped over the survey area. Morgan et al. (2018) describe the detailed processing techniques for FTG data on this project. Fig. 4 displays the Tzz map of the survey.

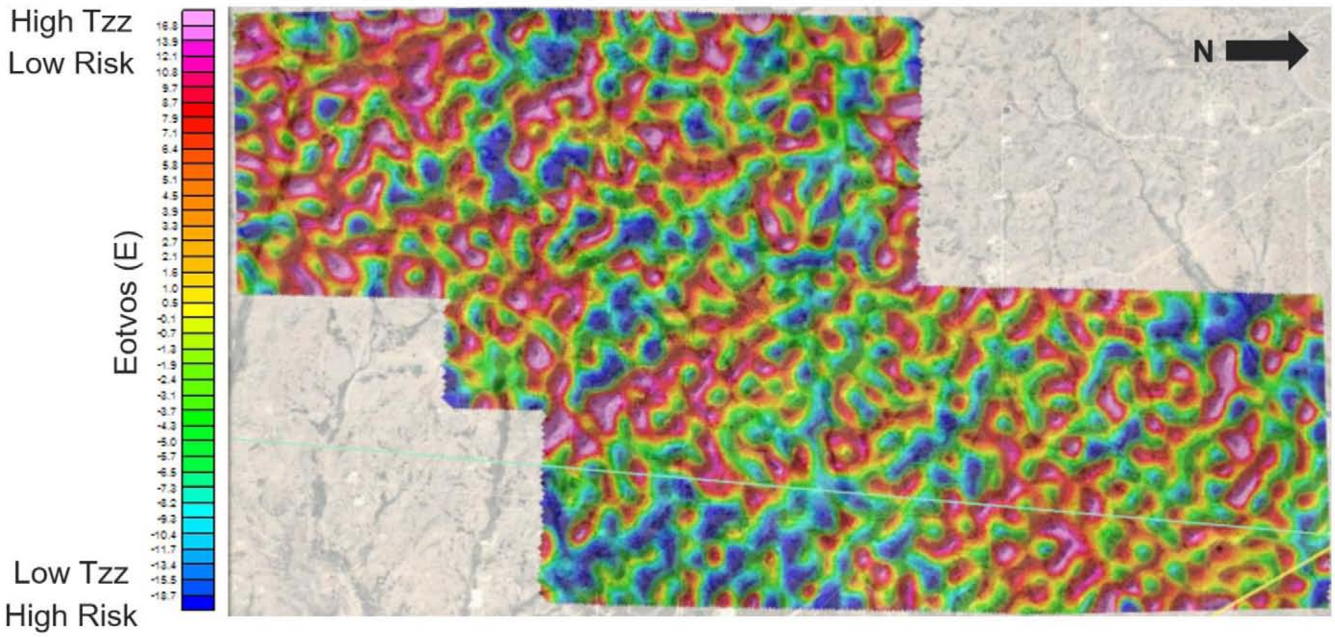

Figure 4—Survey Area Tzz Map on Top of Google Earth imagery.

The areas of Tzz minima, in blue, were expected to be at the highest risk for caves and drilling losses, and assigned elevated risk. The elevated risk label includes any section containing the salient features to the main lineament of the cave system. Moderate risk areas include the elevated risk sections with an added buffer of several hundred feet.

The offset wells locations were then loaded on to the Tzz map. None of the twelve offset wells drilled inside an area assigned elevated risk. Most of the offset wells drilled near Tzz maxima. However, the areas of Tzz minima represent a small percentage of the study. Fig. 5 displays six of the offset well locations and their respective Tzz shading.

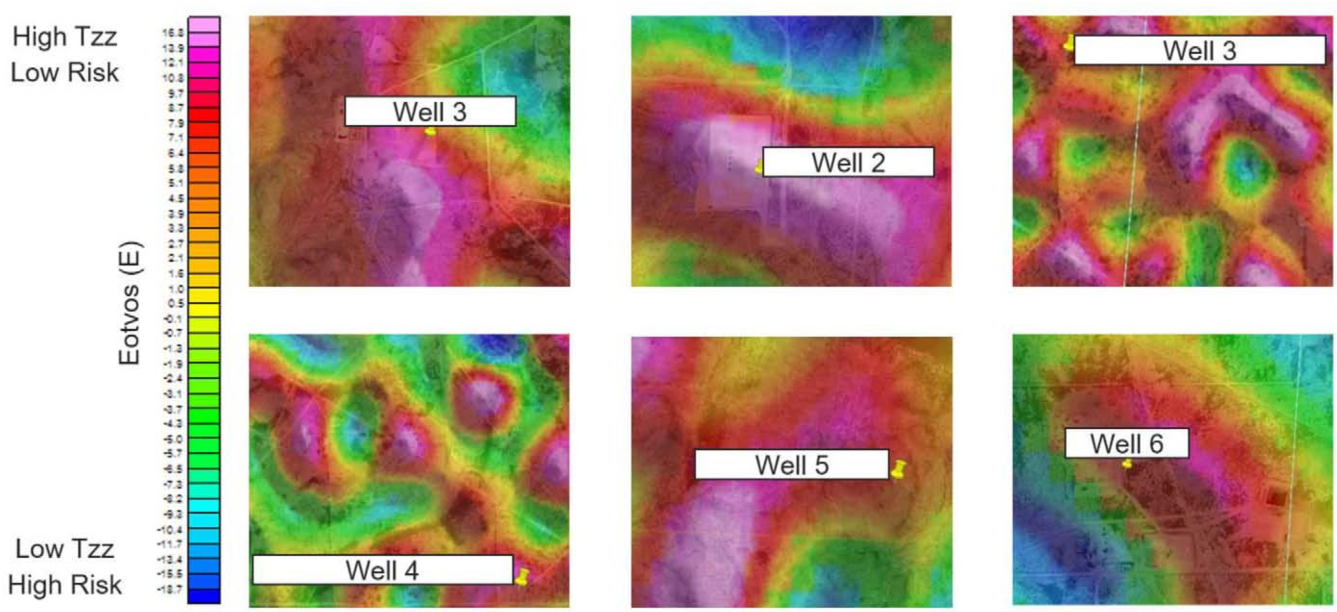

Figure 5—Tzz Values for Six Offset Wells on Top of Google Earth imagery.

Pad A and B are located in elevated risk along a subsurface cave system. This provided positive correlation of the drilling losses interpretation of the FTG data. Fig. 6 shows a satellite image of Pad A/B and Fig. 7 shows where Pad A/B sit on the FTG interpretation.

Figure 6—Pad A/B Satellite Photo from Google Imagery.

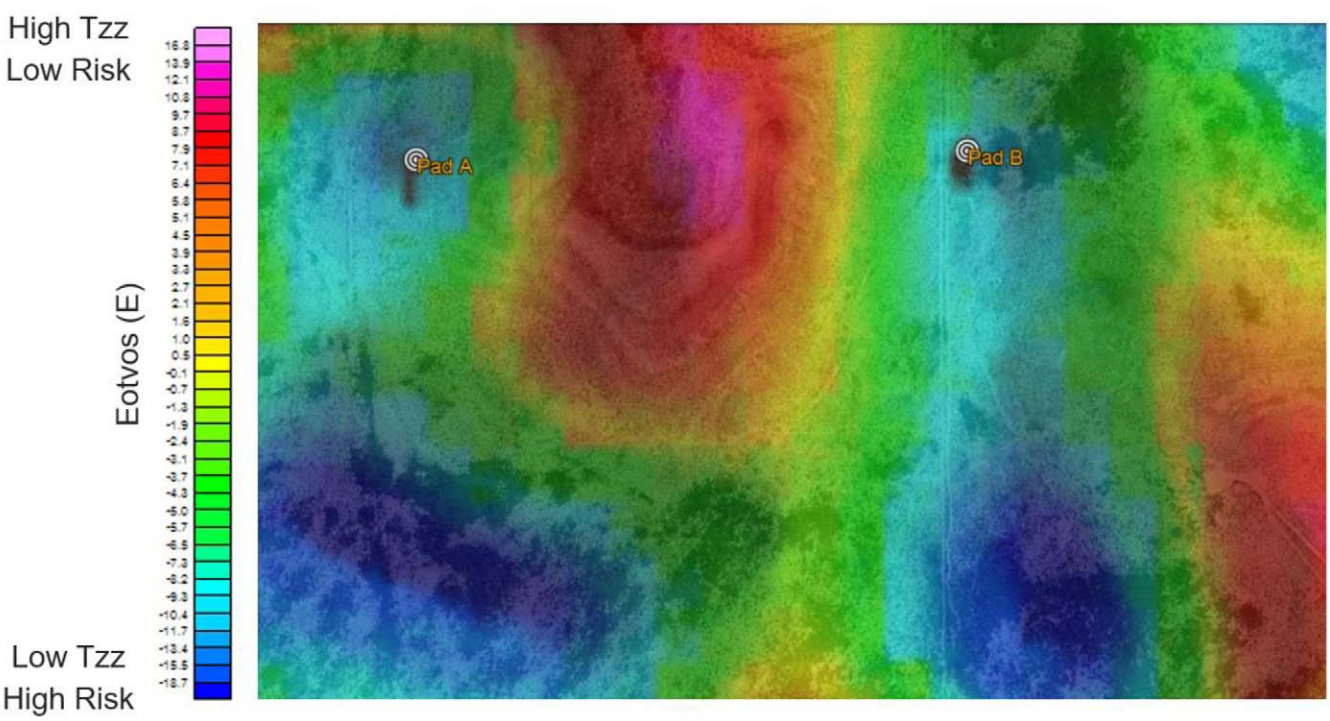

Figure 7—Pad A/B FTG Interpretation on top of Google Imagery. Colors are Tzz.

While drafting this preliminary FTG interpretation two more pads began drilling. Pad C was assigned a moderate risk for losses and Pad D was an assigned elevated risk for losses. The service company elected to advise the Operator of the risk for losses on Pad D despite the preliminary state of the FTG interpretation at the time. No losses occurred drilling either Pad C or Pad D.

These extra data points led the gravity interpreters to revise the interpretation. Fig. 8 shows Pad D with the new interpretation to produce a moderate risk classification. In this final interpretation elevated risk areas are colored blue and moderate risk areas are colored white.

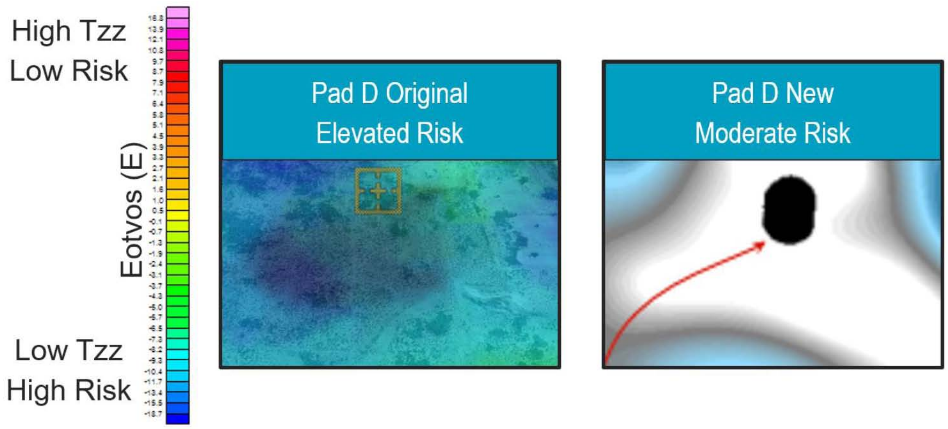

Figure 8—Pad D New Risk Interpretation from Elevated to Moderate. Moderate Risk Areas in White on the right image.

The location of a final drilling pad, Pad E, pointed to an elevated risk for losses. Losses did occur on Pad E resulting in abandonment of the wellbore and construction of a new conductor near the existing pad, providing validation for the new FTG interpretation. Fig. 9 shows Pad E with the final interpretation and elevated risk classification for Pad E.

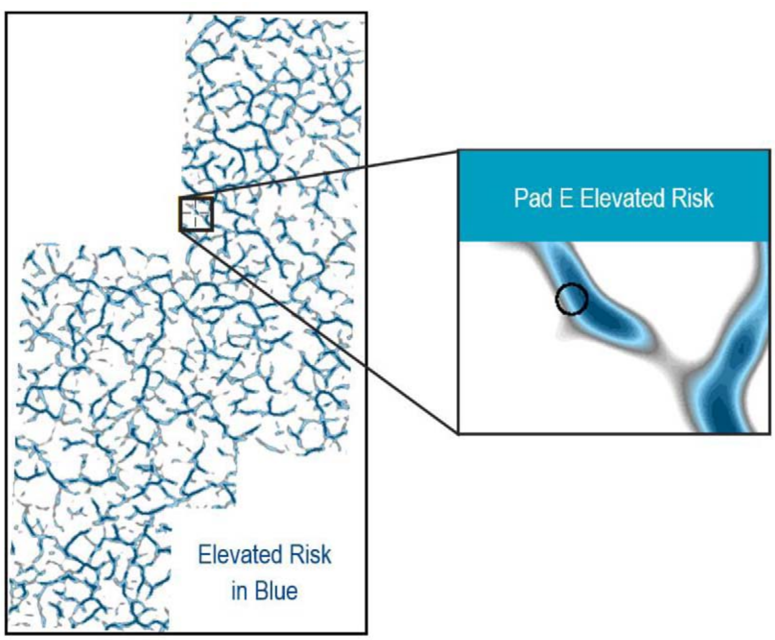

Figure 9—Pad E Final Interpretation.

Future Advancements

Several avenues exist to improve the regional hazard mapping. First, the FTG study area can be increased by picking up more data through more flights. Picking up more data increases the capture aperture of low frequency gravity tensor data improving the depth of investigation. For drill pads geographically restricted to elevated risk a more detailed pad specific seismic study is an alternate, and likely more costly, technique.

Conclusion

Despite the unexpected cave system penetrated on Pad A and Pad B drillers did mitigate the losses and circulate cement to surface successfully using various techniques. However these mitigation steps increased time and cost of the batch sets significantly. Given the size of the loss zones, effectively caves, LCM was ineffective in controlling the losses. A stage tool is an inefficient tool to lift cement through the caves experienced here when placed near or below the loss zone. Cement plugs offer a better solution to fill up the caves although there are risk considerations. The intermediate cement plug set in open hole after drilling past the loss zones held circulation for less than 100 ft of MD drilled.

The best solution is to recognize the risk to drill into caves before building the pad. Gravity FTG data, combined with careful interpretation, offers a strong correlation to known shallow hazards and cave systems, making it an important tool for risk assessment. The FTG data and interpretation is a systematic hazard mapping tool superior to legacy techniques and anecdotal evidence.

This is the first application of FTG to classify drilling risk of karst features in the Permian basin. The FTG hazard map improves operational integrity of surface location selection, an improvement the Operator found to be valuable. Further refinement to this hazard mapping solution is continuing. The FTG data and interpretation also hold value for fault mapping and for water drilling efforts. Airborne gravity FTG is a cost-conscious method to control the risk of drilling into caves over a large geographic region.

Acknowledgements

The authors with to thank the Operator and the many people who helped this project execute safely and successfully. The authors also with to thank Steve Hann for his support backing the FTG project.

SI Metric Conversion Factors

ft × 3.048* E–01	= m
ft^2 × 9.290 304* E–02	= m^2
ft^3 × 2.831 685 E–02	= m^3
gal × 3.785 412 E–03	= m^3
in. × 2.54* E+00	= cm
in.^{2} × 6.451 6* E+00	= cm^2
in.^{3} × 1.638 706 E+01	= cm^3
kip × 4.448 222 E+03	= N
lbf × 4.448 222 E+00	= N
lbm × 4.535 924 E–01	= kg
mile × 1.609 344* E+00	= km
bbl × 1.589 873 E–01	= m^3
gal × 3.785 412 E–03	= m^3
mL × 1.0* E+00	= cm3
psi × 6.894 757 E+00	= kPa

*Conversion factor is exact.

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