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Drilling Deep into New Mexico's Proterozoic Basement

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ABSTRACT

In 2022, Eavor Inc. (Eavor) completed drilling the Eavor-Deep™ demonstration well in southwest New Mexico, USA. The demonstration borehole successfully tested Eavor drilling technologies deep into the hot Proterozoic granitic basement, reaching a total depth (TD) of 18,000' true vertical depth (TVD). Understanding the stratigraphy and rock properties of encountered formations is critical to drill bit selection, casing design, and thermal modelling, in-service of Eavor-Loop™ development. Developing a drilling prognosis was challenged by poor seismic imaging below the shallow Tertiary Volcaniclastics, comparatively shallow local well control, a major fault zone and generally few deep Proterozoic basement penetrations in the boot heel of southwestern New Mexico.

Regional maps, field studies, local well control, magnetotelluric surveys and seismic surveys were integrated into a 3D geological model. A probabilistic geological prognosis was generated using a multi-discipline structural uncertainty workflow to characterize the positional uncertainty of both the Animas Valley fault system and geological formations down to the top of the basement. The encountered geologic formations, and faults were reasonably predicted in the uncertainty model allowing for adequate casing design and bit size and type selection.

Once intersected, the Proterozoic basement rock heterogeneity was further assessed through cuttings data from this well, complimented by outcrop studies at select Arizona and New Mexico locations. The outcrop analysis aided in generating a better concept model of the Proterozoic which helped to further understand changes in rock properties that contributed to bit pull/push along with challenges related to bit longevity and maintenance of adequate drilling parameters for drilling efficiency.

One possible structural-stratigraphic model for the Proterozoic involves back arc marine sedimentation environment that was intruded by monzogranitic plutons and subjected to metamorphism and deformation associated with the Mazatzal orogeny. Following this, syenogranite intruded the deformed monzogranites and metasediments and the full package was subsequently further metamorphosed by the Grenville orogeny. Further study involving acquisition and incorporation of additional deep borehole data, imaging data, thin section analysis

and age dating is recommended to further understand the subsurface structure, stratigraphy and emplacement age relationships of the Proterozoic section below southwest New Mexico for the purpose of supporting future deep drilling projects.

1. Introduction

Eavor Inc. (Eavor), a Calgary based technology company, aims to expand the geothermal operation space beyond the currently accessible conventional hydrothermal and EGS realm. Following the successful Eavor-Loop 1.0 demonstration project at the Eavor-Lite™ facility in Alberta, Canada, Eavor continued innovating on its closed loop design to place an Eavor-Loop in deeper, hotter, basement rock. The new technology required for the Eavor-Loop 2.0 design was recently implemented, drilling a demonstration well in a known geothermal resource area (KGRA) in Southern New Mexico, U.S.A. The successful implementation of these technologies can provide benefit to the geothermal community beyond Eavor's closed-loop systems, allowing for drilling efficiencies and learnings applicable to other high-temperature, hot dry rock (HDR) or enhanced geothermal operations (EGS).

The KGRA is located in the "boot heel" of New Mexico, in Hidalgo County, straddling the basin and range age Animas Valley Fault system. A utility-scale power plant has been producing from this KGRA since 2013 with wells developed in outflow hosted within volcaniclastic strata above the Paleozoic carbonates. A fish hatchery also takes advantage of the thermal waters northeast of power plant's field, producing disease-free tilapia fingerlings. This valley is also home to long-standing local ranchers utilizing the potable water from the Boison and Gilla aquifers, contained within the Quaternary conglomerates, lacustrine and alluvial deposits (O'Brian and Stone 1990). In 2022 the power plant's owner permitted Eavor to drill the Eavor-Deep demonstration well, on the southwestern end of the KRGA, spudded into the hanging wall of the Animas Valley Fault system.

A geologic prognosis of the expected geology to 20,000ft (about 6.1 km) below the KGRA was required to design and drill the Eavor-Deep demonstration well. The planned surface and borehole trajectory of Eavor-Deep required drilling through the local potable water aquifers, the producing area of the KGRA reservoir, and the Animas Valley fault zone, inferred as the host of the up flow of the convective geothermal resource (Elston et al., 1983), making proper casing design based on the geologic prognosis imperative. The geologic prognosis was not only used in designing borehole trajectory and casing points but was also used for borehole temperature modelling, geomechanical evaluation, and drill bit and bottom hole assembly (BHA) selection. As borehole penetration rate and bit life were two of the measurable technology success criteria being monitored in this well, selecting the bottom hole assembly and drill bits suited to the upcoming geology was critical. The borehole temperature prediction built from the prognosis impacts the cooling technology program, the petrophysical and coring data collection for knowing how deep the tools may be run given the operating temperature constraints, and which temperature constrained batteries can be run in the bottom hole assembly.

2. Geologic Model

2.1 Source Data

Generating the geologic prognosis for Eavor-Deep was complicated by the local structuring of the Animas Valley fault zone, along with limited deep borehole penetration and deep imaging data of the lower Paleozoic and Proterozoic sections. The power plant's offset wells were relatively shallow (~6500ft maximum depth), and predominantly targeted the shallow Tertiary - Quaternary volcaniclastic hydrothermal reservoir. These wells (including the proximal 17-7 well) provided a host of shallow subsurface data including mudlogs, and wireline log suites, some with formation microresistivity image logs (FMI). Two wells within 2.5 miles of the Eavor-Deep site intersected the top 10 feet of Proterozoic basement in the footwall of the Animas Valley Fault: the 55-7 Steam Reserve well (55-7 S.R.; TD 7001ft in 1985) and the Cockrel Pyramid Federal well (C.P.F.; TD 7404ft in 1969). Both wells had wireline log suites and the 55-7 well also has a striplog from mudlogging operations. In addition to these borehole penetrations, a 3D drop source geophysical survey (2010) was reprocessed, however the depth imaging was insufficient to identify the geology below the Tertiary. A magnetotelluric (MT) survey was also completed previously in the area and was inverted with additional regional data to construct a 3D model. This 3D inversion provided a better indication of the deeper structure in the area by showing a downward stepping base of a lower resistivity zone (interpreted to be the base of the more porous Tertiary), to the west of the Animas Valley Fault surface expression. Given the nature of MT data, it could not resolve detailed changes in the geology below the Tertiary. Regional gravity and magnetic data also highlighted a structural anomaly aligned with the Animas Valley fault system. Both surveys show a long narrow nose of higher values (in mGal and in nT) with values dropping to the north, east and west. The surface location of Eavor-Deep was located on the hanging wall block, on the west side of the Animas Valley fault zone, at the western edge of the producing area of the KGRA.

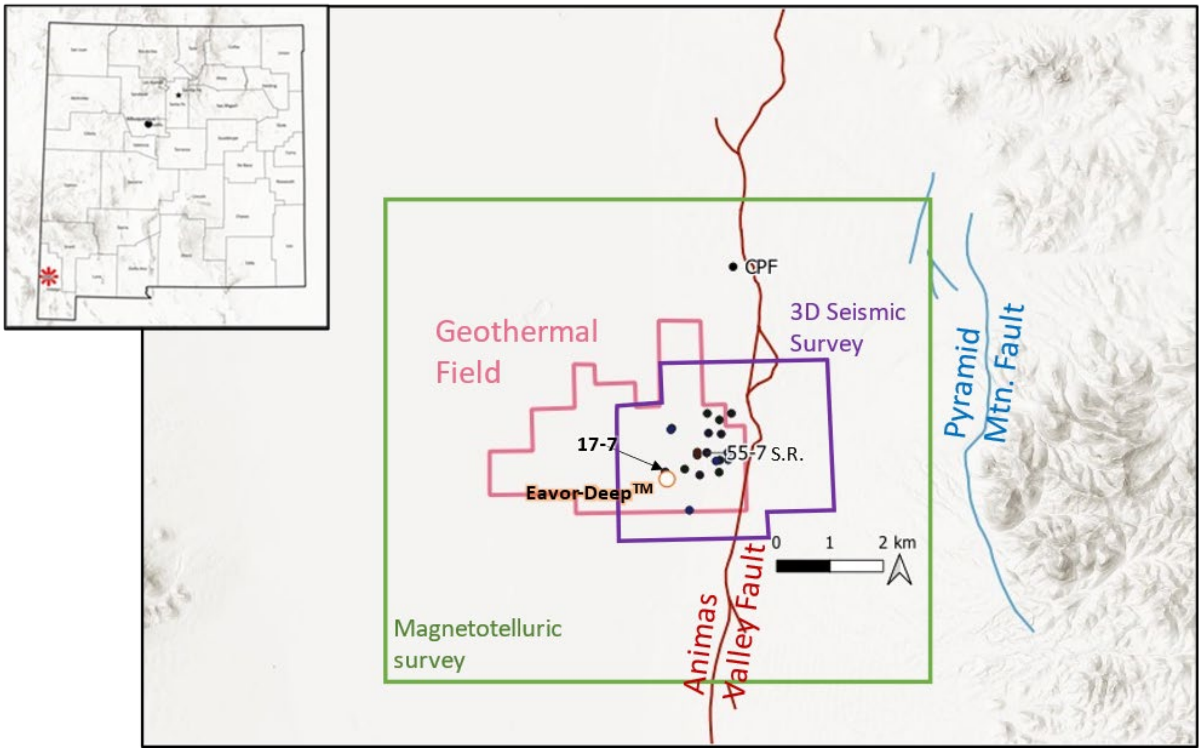

Figure 1 Location of the KGRA (pink), Animas Valley Fault surface trace (red) (Machette & Jochems 2016), and Pyramid Mountain faults (blue), Magnetotelluric survey (green) and 3D seismic survey (purple) and Key wells: CPF (Cockrel Pyramid Federal), 55-7S.R. (Steam Reserve), 17-7 (the power plant's offsetting injection well) and Eavor-Deep demonstration borehole.

2.2 Pre-Drill Stratigraphic framework

The stratigraphy in Table 1 (below), describes the stratigraphic horizons interpreted in the geologic prognosis. These have been grouped into four larger units as described here from oldest to youngest units: Proterozoic basement (target conductive heat reservoir unit), Paleozoic carbonates (deeper area wells terminate in the upper 200ft of the Paleozoic), Cretaceous to Tertiary volcaniclastics and clastics (developed reservoir in outflow of the KGRA's geothermal system), and Tertiary to recent clastics (potable aquifer host unit) for simplicity.

The Proterozoic unit was the target heat reservoir for testing 2.0 technology. Due to limited borehole data intersecting these rocks in this region, sampling of local outcrops was undertaken to understand the Proterozoic basement heterogeneity as it relates to the subsurface. The composition was shown to include Proterozoic mega-crystic to porphyritic granite with some large microcline phenocrysts, along with the Pinal formation which consists of phyllite, quartzite, amphibolite, metavolcanics, and gneissic granite (Drewes 1982, Drewes et al. 1995, Erikson and Drewes, 1984). Multiple granodioritic, mafic and aplitic intrusions are also present within the Proterozoic unit. Major structural events impacting the Proterozoic unit were the Mazatzal (1.65 to 1.6 Ga) and the ensuing Grenville (1.3 – 0.95 Ga) orogenic events (Whitmeyer and Karlstrom 2007). The Proterozoic basement is unconformably overlain by the Coronado/Bliss Cambrian sandstone and conglomerate, comprised of the eroded granitic basement.

The Paleozoic carbonate unit was deposited during a tectonic quiescence, capping the crystalline basement. The Ordovician Montoya and El Paso Formation limestones and dolomites comprise the base of this unit, followed by the Devonian Percha black shale formation. Above this, are the predominantly limestone and minor shale and chert beds of the Escabrosa and Paradise formations. The topmost formation in this unit is the Pennsylvanian Horquilla limestone and shale (Drewes and Thorman 1980). The Permian formations of the Concha, Epita, Colina and Earp formations were not found in offsetting outcrops or well cuttings. This may be due to the erosional upper bound of the Paleozoic carbonate unit, caused by the extensional activation of faults that formed a belt of northwest-southeast trending extensional basins collectively referred to as the Border Rift faults (Clinkscales and Lawton, 2018).

The upper volcaniclastic and clastic units are host to the Gilla and Boison aquifers as well as the power plant's producing geothermal aquifer. At the base of this unit the Late Jurassic to Early Cretaceous Bisbee group is differentially preserved, due to the extensional activation of the Border rift normal faults, followed by reverse fault movement caused by compression during the Laramide orogeny (80 to 50 Ma). Above this, Eocene to Oligocene andesitic lavas and tuffs associated with local calderas, (including the offsetting Muir caldera, 35Ma) were emplaced during an ignimbrite flare-up that travelled east to west across New Mexico and Arizona (~37 to 26 Ma) (Elston et al., 1983). Next, there was syntectonic deposition of variable thickness, undifferentiated, Paleogene to Pleistocene volcaniclastics, conglomerates and clastics associated with Basin and Range extensional faulting, including the Animas Valley fault zone. The onset of this faulting in the Basin and Range/Rio Grande Rift transition area initiated about 25 Ma, with a major episode of extension continuing to about 14 Ma and continuing at slower rates possibly over a smaller areal extent to present time (Ricketts et al., 2021). Capping the previous volcaniclastic unit, are the Quaternary Gilla conglomerate, recent lakebed sediments and recent alluvium.

Table 1 End member stratigraphic model down to 20,000ft at the KGRA based on outcrop and offsetting wells, key horizons interpreted in the Geomodel are shown in Model Horizon. Formations and map units from Drewes et al.,1980, 1985, and 1995

Unit	Age	Model Horizon	Formation	Description
Clastics	Recent	DEM	Alluvium and basin fill sediment (Qa)	Unconsolidated alluvial fill: Alluvium, lacustrine sediments, clay, silt, sand, gravel
	Pliocene to Pleistocene	*Q_Gilla_LL*	Gila (Qg)	conglomerate of chiefly schist or granite and lesser dacite, diabase, and quartz, sand and clay interbeds
Volcaniclastics	Mioceneto Pleistocene	~T_MVOL_LL	Volcanics and basin fill sediment (Tksv)	Pliocene volcanics, Sandstones and clay
	unconformity - Related to Basin & range extension			
	Paleogene	*~T_LVOL_LL*	undifferentiated sedimentary and volcaniclastics (Tksv)	Volcanic conglomerate with interbedded sandstone, tuff, tuff breccia, and dacitic lava
	Paleogene	unpicked	Intrusive dikes (Ti)	Qtz rich granitoid, Monzogranitic, Qtz syenitic intrusions (Rhyolitic)
	L.Eocene to L.Oligocene	T_TUFA_LL	Tuff (Tt)	Andesitic Lava, Tuff, Volcaniclastic sediments and breccia, Muir Caldera Deposits
	unconformity - related to Laramide Orogeny reactivation of Border rift faults			
	L. Jur to E.Cretaceous	K_BSBS_LL	**Bisbee Group (Kb);** *Cintura Formation (Kc), Mural Limestone (Kmu), Morita Formation (Km), Hell-to-Finish Formation (Kh), Glance Conglomerate (Kg)*	Shale, siltstone, sandstones, conglometrates and limestones
Carbonates	*unconformity - related to Cretaceous extension on Border rift faults*			
	Permian	unresolved, absent in mapped outcrops	Concha Limestone (Pcn), Scherrer Formation (Ps), Epitaph Dolomite (Pe), Colina Limestone (Pc), Earp Formation (Pea)	Limestone, sandstone and dolomite
	Hiatus			
	Pennsylvanian	P_HQLA_LL	Horquilla Limestone (Ph) (PPh, Phu, and Phl)	Limestone to shaley limestone with sandstone beds occasional dolomite
	Mississippian	M_ECBA_LL	Paradise/Escabrosa (Me)	Massive to thin bedded Limestone and dolostone some chert beds
	Devonian	D_PCHA_LL	Percha (Dp)	Shale with siltstone interbeds
	Hiatus/ Unconformity			
	Ordovician	O_MTEP_LL	Montoya (Om)	Argillaceous limestones and dolomite
	Ordovician	undifferentiated	ElPaso (Oe)	Limestone to dolomitic limestone, sand beds at base
	Cambrian	E_BLISS_LL	Bliss (Eb)	Sandstone with limestone interbeds, conglomerate at base
Proterozoic basement	*unconformity - related to acretionary tectonics and Mazatzal and Grenville orogenies*			
	Precambrian	Y_GRNT_LL	Granite intrusions and plutonism (Yg)	Monzogranite to syenogranite with porphyritic to megacrystic texture
	unconformity - related to accretionary tectonics onset of Mazatzal orogeny			
	Precambrian	unresolved	Pinal Schist (Xp)	accretionary formation: quartzite, schist, amphibolite to gneissic granite

2.3 Structural Framework

The depth of the top of Paleozoic strata and thickness of the overlying Mesozoic strata vary substantially across the power plant's well field over a distances of < 2 km. There is an overall deepening of the top of Paleozoic strata from the east to the west, but it is also not a linear trend. This pattern is consistent with fault offsets through the field, including with possible tilted fault blocks (e.g., strata are not flat lying) and has implications for potential fault intercepts from ground surface to TD of 17-7 and from TD of 17-7 to 23,000 ft total depth (Figure 1).

The generally N-S-striking, west dipping Animas Valley fault system is the only fault in the power plant's well field area with known surface exposures over some segments (Figure 1). There are multiple depictions of the surface trace(s) of the Animas Valley fault system (Drewes et al., 1985; USGS, 2016) and multiple models of the number of fault splays and dips of respective fault splays (Blackwell and Wisian, 2001; Cunniff and Bowers, 2003; GeothermEx, 2005). In general, these models are consistent with a down-to-west, N-NE-striking normal fault system, but with variable number of splays, geometry of how the splays merge or diverge, and the stratigraphic offset across specific faults.

2.4 Concept Geomodel

A 3D geologic model was built utilizing the described dataset in Aspentech's SKUA™ and SeisEarth™ software packages. The model focused on interpreting the key horizons outlined in Table 1, with the exception of the Permian strata, as these units were not believed to be encountered in offsetting wells.

Within the geothermal field, borehole penetrations of the top Paleozoic align with the less resistive zone on the MT survey. The base of this less resistive zone on the MT was used to help extrapolate the top of the Paleozoic between and beyond the well penetrations. Regional formation thicknesses were assessed in order to map the surfaces below the base of the Tertiary away from well control. In comparison, the Paleozoic formation thicknesses intersected in the Cockrel Pyramid Federal well were varied, but approximately 70% of the interpreted formation thicknesses from the USGS Misc. Field Studies Map I-1221 (Drewes and Thorman 1980). The 55-7 Steam Reserve well Paleozoic formations were varied by approximately 1.5 times the thickness interpreted illustrated in the Misc. Field Studies Map I-1221. The borehole FMI data, and the thicker than anticipated Paleozoic package was interpreted to indicate dipping strata penetrated by 55-7 S.R. well. Given this, the Paleozoic formation thicknesses used to extrapolate formation surfaces below the base of the Tertiary, away from well control, were within the range of the C.P.F. well and thicknesses determined from USGS Misc. Field Studies Map I-1221. It was understood that erosional unconformities associated with the Paleozoic could result in overly deep surface interpretation, however additional confining data was unavailable.

To interpret the faults in the model, borehole mudlog descriptions, petrophysical logs and formation micro imaging logs from the power plant's wells were used. Extrapolation beyond well penetrations of the shallow faults involved projecting fault planes from borehole intersections using FMI strike and dip, incorporating the surface traces of the Animas Valley and Pyramid

Mountain faults from the USGS fault data base, and interpreting steps/offsets of the base of the MT survey low resistivity zone interpreted to be the base Tertiary/top Paleozoic.

Four main Animas Valley faults were interpreted, using the methodology explained above. Given the sparse deep dataset, and the complexity of Basin and Range fault systems, it was understood that the interpreted faults would represent only a portion of the existing possible faults within the Animas Valley fault zone. Few wells penetrate the Proterozoic strata locally, therefore only the Proterozoic surface was included in the model, and not the discrete heterogeneity within. The model and cross-section below illustrate the concept geomodel generated for the area based on available data.

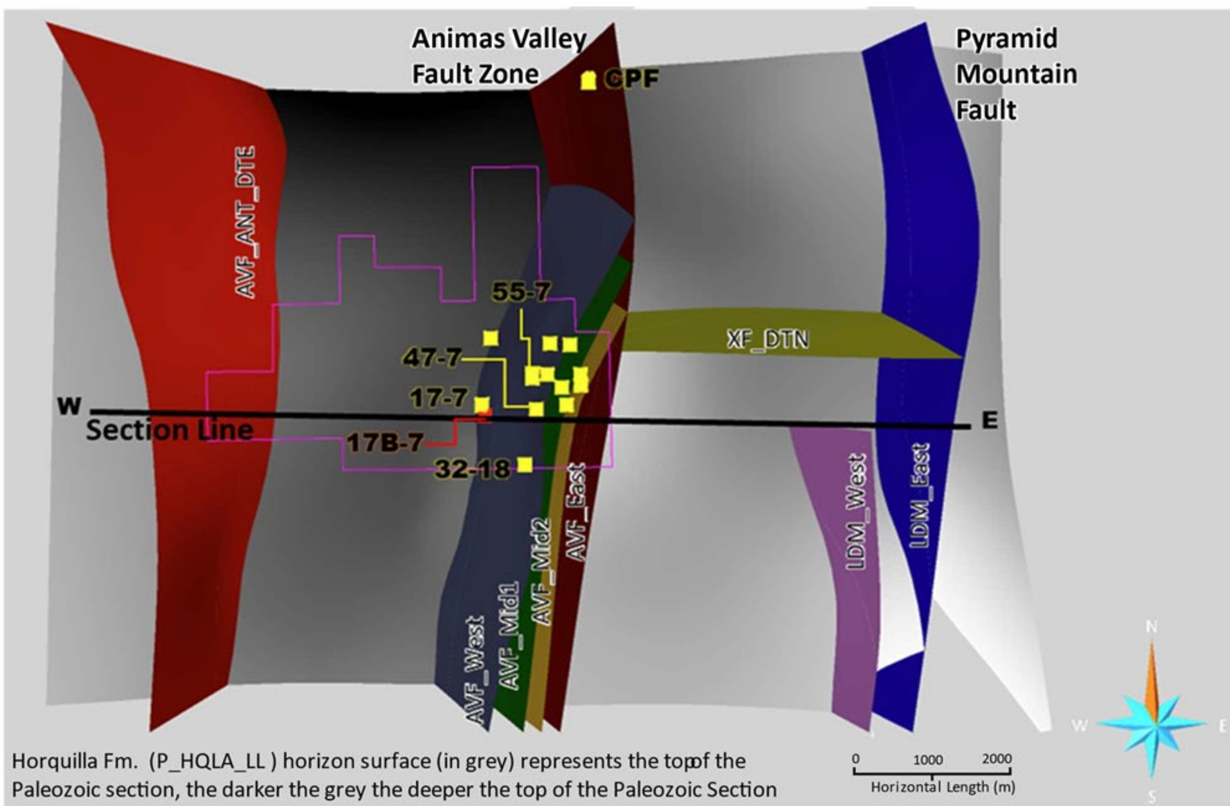

Figure 2 Map view of the concept geomodel, based on the interpretation of the available dataset, showing the interpreted faults and the Horquilla Fm. (Paleozoic top) horizon surface. A west to east section slices through the KGRA, shown as a black line, which correlates to the section below. Key wells used in model development are labelled.

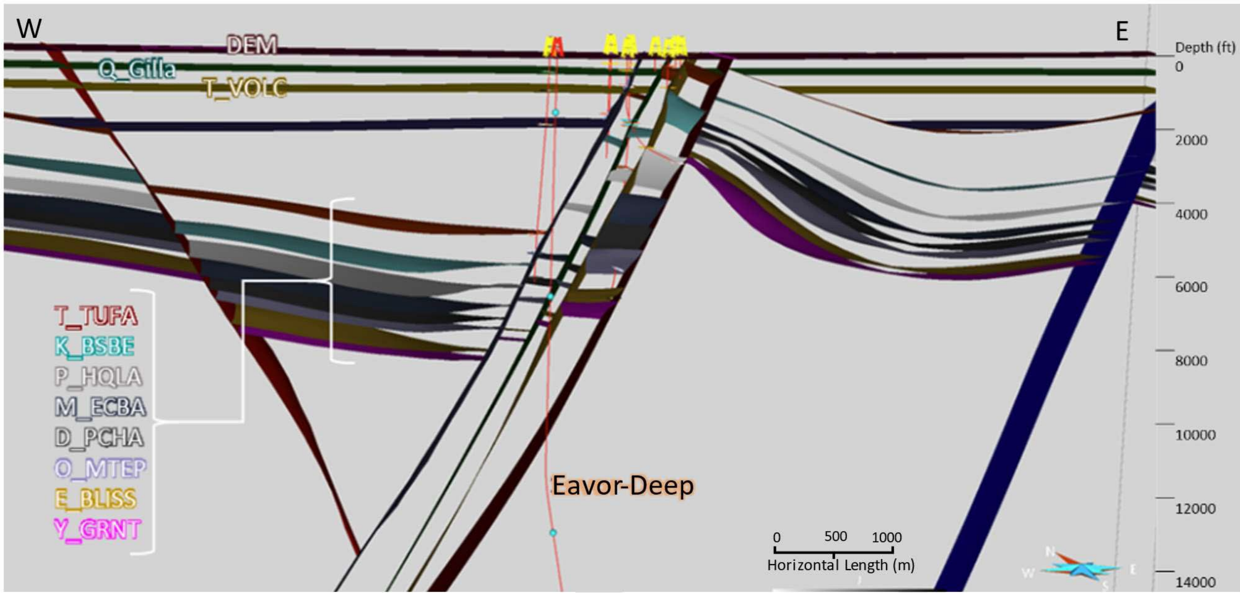

Figure 3 West to East section slice through the KGRA showing Eavor-Deep planned well trajectory, faults, and model horizons. P-HQLA (white lettered) represents the top of the Paleozoic surface as identified in Table 1. Other interpreted horizons abbreviations can also be found in table 1. The four faults in the center of the section represent the Animas Valley Fault zone.

3. Uncertainty Modelling

3.1 Permutation Parameters

During the creation of the geomodel, the uncertainty in position and depth of structures below offset well data was identified to be very high. Further uncertainty modelling was required to gain a better understanding of the probability of structural outcomes to feed into the geological prognosis. In a preliminary field outcrop study, it was noted that the Percha shale was a possible source of borehole instability, and that the landing of the 13 3/8 inch casing shoe should be done below this formation. Additionally, the Animas Valley Fault system was to be isolated completely by the 9 5/8" cemented liner to seal off any open fault permeability, in the interest of maintaining a closed system. Finally, with the more aggressive bit design required to drill the Proterozoic granite, there was a need to determine if a 17 ½ inch granite capable bit was required on site in addition to the 12 ¼ inch and 8 ½ inch bits needed for drilling the deeper section.

Uncertainty modelling was implemented to better understand the range of possible outcomes given the uncertainty surrounding the deeper strata, the Animas valley fault system projection, and the importance of the prognosis to effective borehole design. An uncertainty modelling workflow (figure 4.) was designed to capture the uncertainty on (1) the location of the Animas Valley faults at depth, (2) the range in formation thickness seen in wells and outcrop, and (3) the difference in the Proterozoic basement depth between the interpreted geomodel and a set of seismic high amplitude picks thought to be either the Paleozoic - Proterozoic Basement contact or heterogeneity within the Proterozoic.

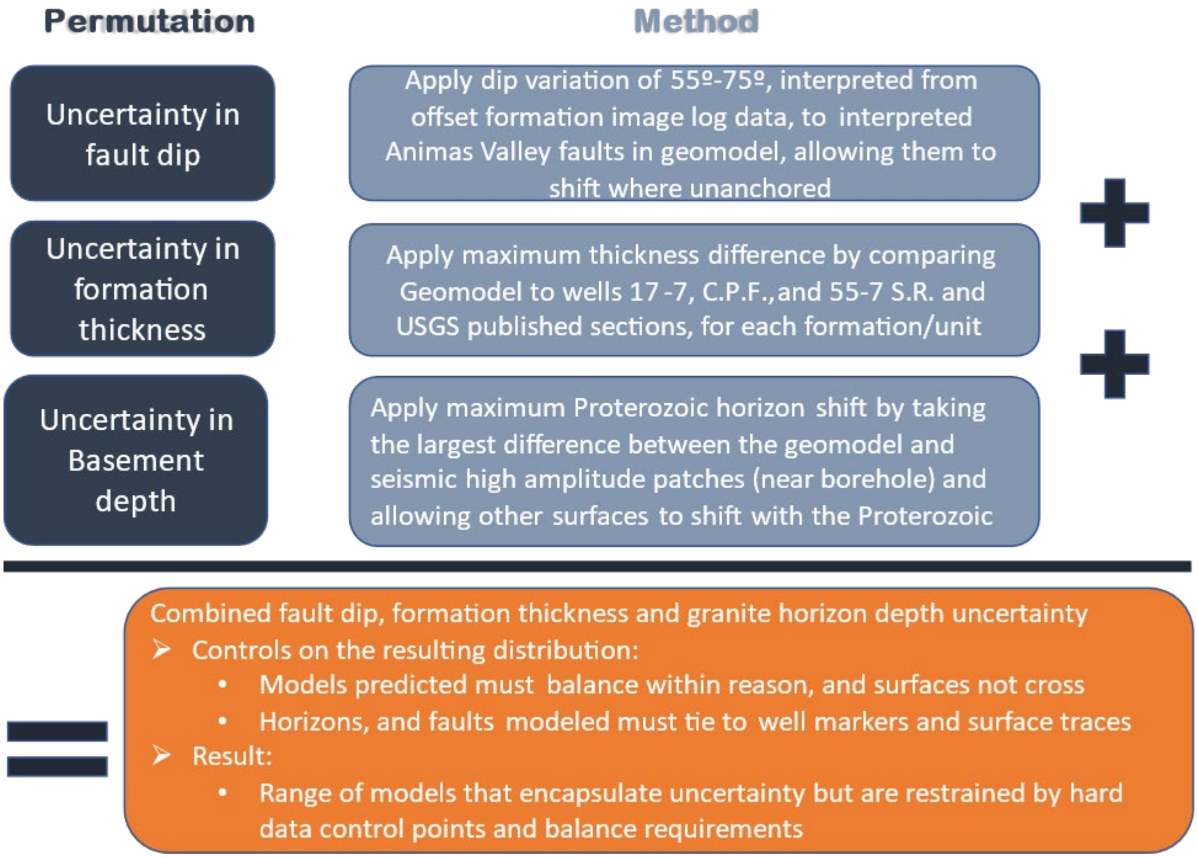

Figure 4 Diagram showing the workflow for each permutation used in generating the uncertainty model.

The dip uncertainty was applied by holding borehole intersections and the surface trace of the main Animas Valley fault (Machette & Jochems 2016) constant, while allowing the faults to move to accommodate the dip range at depth. Known fault intersections from well penetrations were also used as control points, limiting the lateral variability in the fault realizations. The range of modelled dip angles was based on confidential FMI data provided by the power plant owners on 5 of their field wells. The range of 55° to 75° dip of the Animas Valley fault system was selected to encompass the interquartile range of this dataset. An example of the spread of uncertainty realizations, around the eastern most Animas Valley Fault of the concept geomodel, is shown in figure 5.

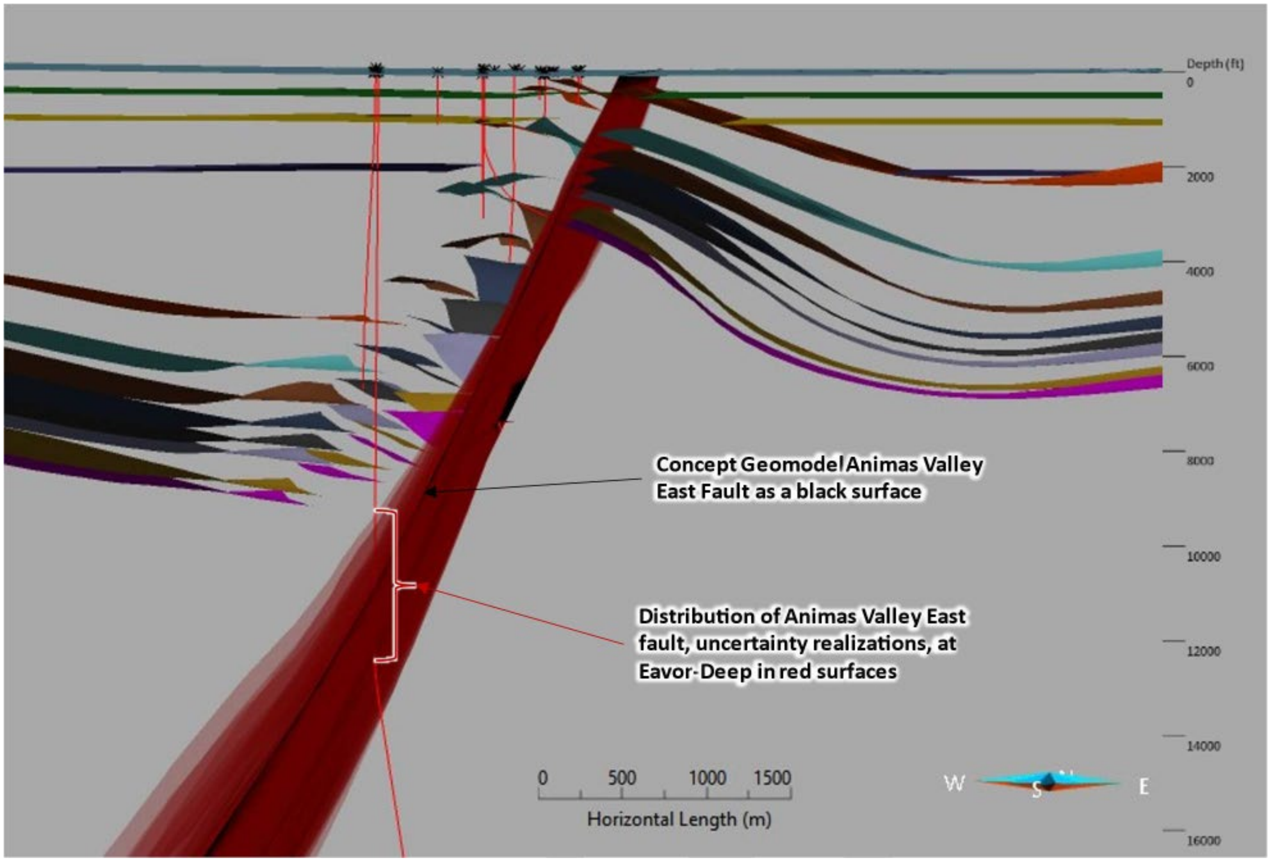

Figure 5 Fault Uncertainty Model Results: Section view of the planned Eavor-Deep borehole, showing the concept geomodel eastern most Animas Valley fault in black, along with the east Animas Valley fault uncertainty realization surfaces in red. Note the increase in spread of the uncertainty realization fault surfaces away from well control points within the KGRA field.

Formation thickness permutations were based on the known isopachs from wells 55-7 S.R., 17-7 (offsetting power plant injection well), and CPF (Cockrell Pyramid Federal), in addition to the USGS mapped formation thicknesses from the Peloncillo mountains. Differences were calculated using the geomodel formation isopachs compared to the CPF, 55-7, 17-7, and USGS maps. The geomodel isopach range was typically between the CPF well and USGS mapping formation thickness. Well formation top intersections were used as fixed control points in the geomodel. The absolute differences between the geomodel and the well/map values were assessed to select the maximum difference. This number was divided by the geomodel thickness value, to generate a permutation factor. This allowed the geostatistical algorithm to increase or decrease the thickness of each formation, within the defined permutation range, to generate simulated surfaces. The result (Figure 6) provided a distribution of surface realizations, honoring the control points surrounding the geomodel surface.

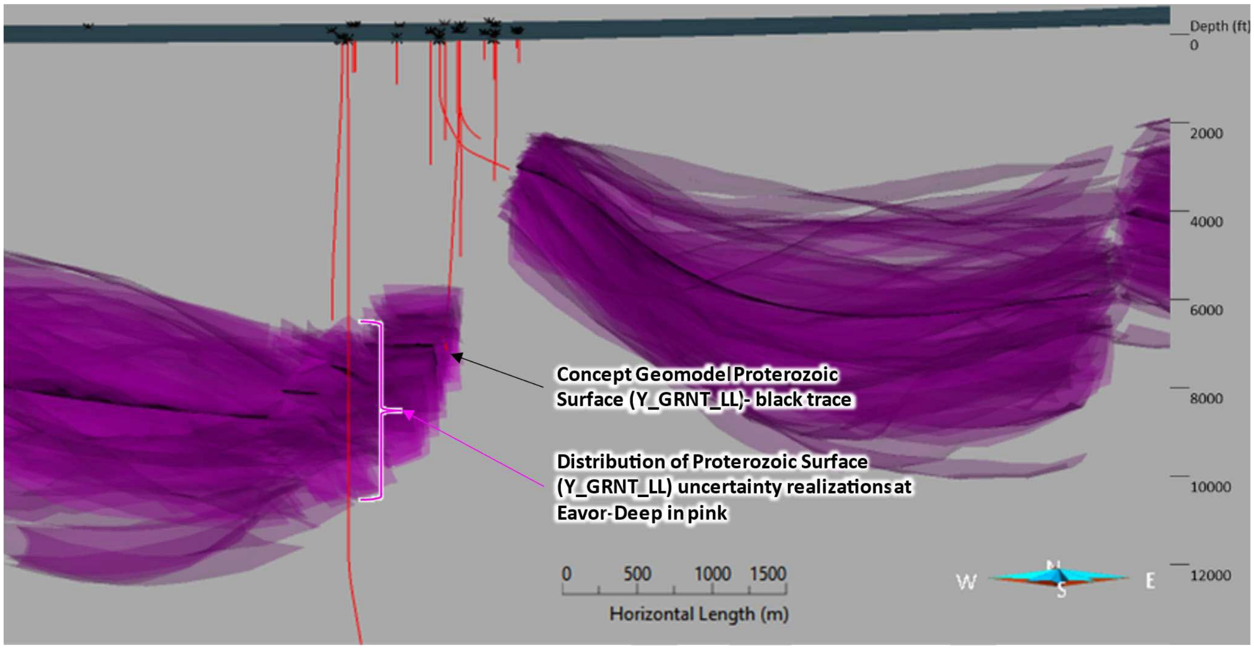

Figure 6 Formation Thickness Uncertainty Model Results: Section view of the planned Eavor-Deep borehole, showing the concept geomodel Proterozoic surface interpretation (Y_GRNT_LL) in black, along with the Proterozoic uncertainty realization surfaces in pink. Note the increase in spread of the uncertainty realization surfaces away from well control points within the KGRA field.

The depth shift permutation was created to account for high amplitude picks interpreted from the seismic 3D volume. These amplitudes could represent the Proterozoic basement surface, Tertiary intrusions, or metasediment rafts. Due to the deep imaging issues in the seismic, major horizons beyond the Tertiary Tuff (represented in 17-7 and 55-7 S.R.) could not be mapped. To provide a geophysically sourced permutation on possible Proterozoic basement depth, high amplitude bodies were interpreted and extracted from the seismic volume, where interpretable, and converted to depth (using a velocity model based on wells 17-7 and 55-7 S.R.) for comparison. The high amplitude bodies were not interpretable as a surface due to poor imaging and instead provided variable patches. In general, the high amplitude patches came in lower than the modelled depth of granite, although it straddles the modelled granite in places (figure 7). The well formation intersections were still used as control points in this depth shift.

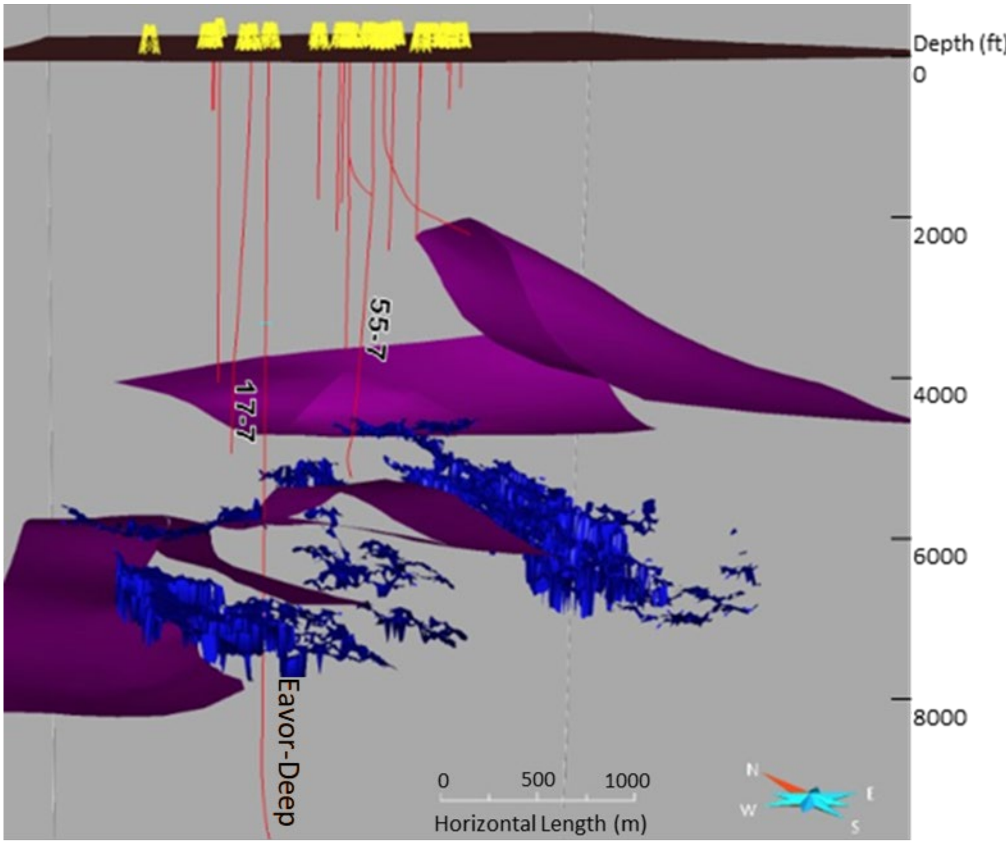

Figure 7 Image of high amplitude bodies from the 3D seismic volume are shown in blue, and the concept geomodel Proterozoic basement surface (Y_GRNT_LL) is shown in pink.

The maximum depth difference, between the concept geomodel Proterozoic surface, and the interpreted high amplitude patches was 1600 feet near the proposed 17B-7 location. This value was used as a maximum depth shift permutation on the concept geomodel Proterozoic surface. All other formation surfaces were allowed to trend along with this to prevent cross-over and model failure, where they were not anchored by borehole intersections. The result of this control input was to generate deeper Proterozoic basement scenarios.

3.2 Uncertainty Modelling Outcomes

The combinations of the fault dip, formation thickness, and Proterozoic basement depth shift permutations resulted in 60 successful simulations out of 250 run simulations. The full compounded uncertainty permutation ranges were not all successfully realized due to the uncertainty modelling success/failure criteria. Successful outcomes had to match the control points in well markers and the models still had to structurally balance without surfaces crossing. Despite this, it was assumed the 60 successful realizations captured a sufficient distribution around the concept geomodel to develop an uncertainty prognosis. Each simulation was reviewed, and formation fault intersection points were captured in a table. The summary statistic table is shown below in feet, compared to the concept geomodel.

Table 2 Uncertainty simulation results of the Geomodel showing the statistical analysis of the formation intersection type and depth at the projected Eavor-Deep demonstration borehole.

Formation or Fault	Geomodel		Uncertainty Realizations TVD Feet							
	TVDFT	Intersection type	P10	P90	P50	Average	Min	Max	% Formation Not Penetrated	% Intersection through fault
Q_Gilla_LL	452	Formation Top	152	752	452	480	50	995	N/A	N/A
T_MVOL_LL	944	Formation Top	644	1244	944	1098	600	2059	N/A	N/A
T_TUFA_LL	N/A	Not Penetrated	4289	4424	4394	4366	4239	4437	88	0
K_BSBE_LL	N/A	Not Penetrated	4659	4659	4659	4659	4659	4659	98	2
AVF_West	4497	Fault	4440	4600	4481	4504	4410	4757	0	N/A
P_HQLA_LL	4497	Intersection through fault	4434	4643	4479	4512	4341	5049	3	90
M_ECBA_LL	5345	Formation Top	4732	6335	5249	5395	4466	6828	0	5
D_PCHA_LL	6025	Formation Top	5337	7102	6027	6115	4950	7525	2	2
AVF_Mid1	6319	Fault	6292	6610	6371	6419	6257	6728	0	N/A
O_MTEP_LL	6319	Intersection through fault	5762	7242	6319	6414	4510	8015	14	8
E_BLSS_LL	6934	Formation Top	6392	7965	7134	7141	6248	8202	29	15
AVF_Mid2	7212	Fault	6853	8104	7544	7497	6389	8398	0	N/A
Y_GRNT_LL	**7212**	Intersection through fault	6642	8104	7471	**7424**	6389	8398	0	44
AVF_East	10376	Fault	9732	11271	10767	10641	9121	11845	0	N/A

Table 2 shows the horizon label as described in Table 1 in the left most column, followed by the geomodel depth, and an indication if the planned Eavor-Deep borehole will intersect the formation through a faulted contact or through the surface contact with the overlaying unit. In the “Uncertainty Realization TVD feet” section, the intersection of the Eavor-Deep borehole with the 60-uncertainty model permutated horizons is expressed in chance of occurrence for the displayed depth. For example, 10 percent of model cases will have intersected the Q_Gilla_LL formation by a depth of 152 feet, and 90 percent of the modelled realizations will have the borehole intersecting the Gilla formation by a depth of 752 feet. The shallowest interpreted intersection of the Q_Gilla_LL horizon is 50 feet, and the deepest realization is 995 feet. The second last column in this table represents the likelihood of the formation not being penetrated at all, for example, the T_TUFA_LL horizon is not intersected (faulted out) in 88 percent of modelled cases. The last column in the table indicates the likelihood that the borehole will penetrate the formation through a fault, instead of through the contact with the overlying unit, indicating the chance of missing section. For example, the P_HQLA_LL formation was intersected through a fault, incurring some missing section, in 90 percent of modelled cases.

A comparison of the shallowest (left image) and deepest (right image) Proterozoic surface realizations compared to the concept geomodel (center) is shown below in Figure 8. Formation Image showing the shallowest realization, concept Geomodel and deepest realization for the Eavor Deep geology in cross-section west to east.In the shallow realization, formations rise towards Eavor-Deep from well marker anchor points, and the faults have lower dips. In the deep realization, formations dive from well marker anchor points to 17B-7, with steeper faults. The geomodel shows a slight rise from the well marker anchor points and the faults are moderate to steeply dipping. The longest red borehole path in figure 6 below was the proposed Eavor-Deep trajectory.

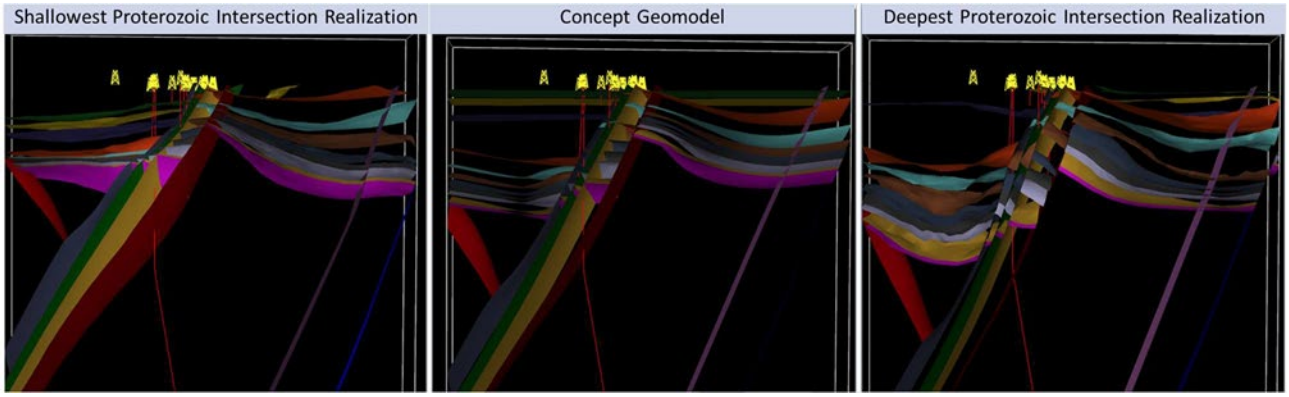

Figure 8 Formation Image showing the shallowest realization, concept Geomodel and deepest realization for the Eavor Deep geology in cross-section west to east.

The uncertainty permutations of thickness and depth shift favor a deeper realization. In addition, the well-control points restrict the realizations from projecting too high, particularly in the shallower Bisbee and Tuff formations. The compounded ability of the depth shift and thickness variations push the Proterozoic surface lower, without the same constraint. This results in a deeper average (~P40) of Proterozoic surface realizations (7424' / 2263m) at 17B-7, compared to the concept geomodel (7212' / 2198m). The P50 depth (7471' / 2277m) is even higher, indicating a deeper skewed distribution. The concept geomodel is therefore approximately a P33 case. Given the predominance of the uncertainty workflow to push interpretations deeper, the conceptual base case geomodel was still believed to be the most geologically viable, it was kept as the expected case. The P10-P90 cases were used to plan for high and low case scenarios to understand casing length requirements, casing shoe landing points and intersection of the top Proterozoic basement for drilling considerations.

3.3 Impact on Geologic Prognosis

The expected prognosis is based on the 17B-7 borehole intersection of the concept geomodel surfaces. The shallow case is based on the 17B-7 borehole intersection of the shallowest realization of all faults and surfaces from uncertainty modelling, and the deep case from the deepest realization intersection at the 17B-7 borehole. The concept geomodel (expected case) intersects the Proterozoic heat reservoir at 7212 feet; the minimum intersection based on realizations is 6389 feet, and the maximum is 8398 feet. The prognosed shallow, expected and deep can be seen in Figure 7 along with the realized geology.

The uncertainty modelling process resulted in the following learnings:

- The Tuff is not intersected (faulted out) in 88% of cases; this matches the geomodel prediction.
- The Bisbee is not intersected (faulted out) in 98% of cases; this matches the geomodel prediction and the missing Bisbee in 17-7.
- 90% of realizations have the Horquilla formation entered through a fault, like the geomodel.
- The Montoya El Paso formation is not intersected (faulted out) in 14% of cases.
- The Bliss formation is not intersected (faulted out) in 29% of cases.

- 44% of realizations have the Proterozoic surface entered through a fault, like the geomodel.
- The geomodel hosts the 6500ft casing shoe in the competent Escabrosa limestone; however, at least 10% of realizations have the 6500ft casing shoe in the Percha shale.
- In all modeled realizations, 13,000'(4000m) casing exceeds the depth of the AVF East fault (Max:11845'). Despite this, the risk of fault intersection could not be removed as unimaged, blind faults farther east of the AVF system could still have existed.

4. Encountered Stratigraphy

4.1 Prognosed Versus Actual

The Eavor-Deep demonstration borehole was spud in August 2022. The landing of the 13 3/8" casing shoe at (6,600ft TVD) below the possibly unstable Percha shale was successful. Having the appropriate casing lengths on site to cover the P90 depth case of the Percha shale, provided the ability to case into the competent Bliss formation at the base of the Paleozoic section. Though some grey silty shale was encountered around 5,300ft MD, it was difficult to discern whether it was the Percha shale, or whether it represented the shalier base Horquilla/Paradise formation above the Escabrosa limestone. Given the position of the shale in relation to the other Paleozoic carbonate units, and the encountered thickness of each carbonate unit. It is thought the shale could belong to the Paradise formation and that the Percha shale may have been faulted out at the borehole intersection as predicted.

The Proterozoic top (6,723ft MD) came in higher than the expected (7,211 ft MD), but well below the shallow case (6,388 ft MD) generated from the uncertainty modelling distribution. The Proterozoic top was identified utilizing borehole cuttings minerology, and both petrophysical and mud logs analysis; no age dating was performed to further confirm the top of the Proterozoic. QEMScan mineralogic analysis from the borehole cuttings and known Proterozoic outcrop samples showed reasonable similarity. Additionally, the depth of intersection and the preceding stratigraphy support the interpretation of this granite as the Proterozoic surface. The high amplitude seismic anomaly patches used for the depth shift of the Proterozoic horizon, appear to be associated more with the deformed metasediment bodies, than the Proterozoic surface. This could explain why they could not be interpreted as a continuous surface. The uncertainty model was used to understand the extent of the variation of granite top and enabled Eavor to have a good understanding of what size of granite capable bits were required on site.

The modelling of the dip variation of the four major Animas Valley fault offsets, determined from shallow well intersections, FMI data, and MT survey interpretation was reasonably successful in identifying the amount of casing to have on hand to isolate the fault zone. Faults encountered above 6,570 ft, where the FMI images were acquired (6,570 ft to 13,118 ft), were interpreted based on fluid loss occurring coincidently with a drilling break and missing section interpreted by comparing borehole MWD gamma with offset gamma logs. Where available, both sonic and resistivity image logs were used to interpret faults alongside quad-combo petrophysical logs, drilling breaks, and fluid losses. It was known pre-drill that each of the four modelled higher offset faults were likely to represent larger fault zones and not unique individual features. Considering this, the encountered fault zones align reasonably well with the pre-drill predicted faults. The Animas Valley fault zone encountered ranged from 4,415ft depth to 11,987ft depth. The upper most fault is within the range of the minimum depth predicted in the uncertainty model (4,410ft MD); the lowest fault encountered (11,987ft MD) is within 150ft of the lowest predicted fault depth (11,845ft MD). Given these results, the pre-drill fault prognosis was successful in helping design the length and landing point of the 9 5/8 inch cemented liner program required to properly isolate the Animas Valley Fault system (i.e., by having the necessary liner lengths on site).

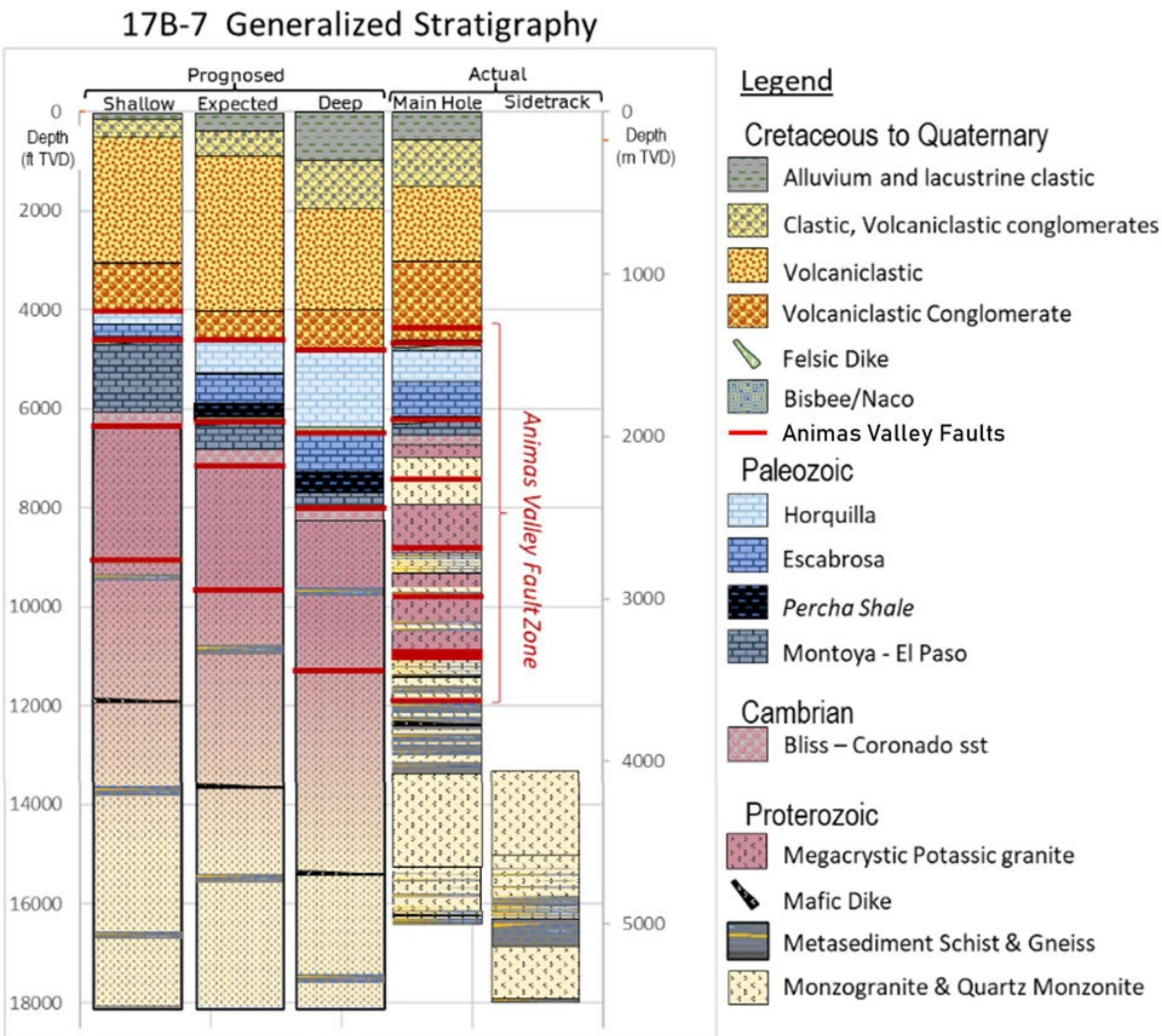

Figure 9 The pre-drill concept geomodel and uncertainty prognosis compared to the encountered geology.

4.2 Proterozoic Outcrop Study

Predrill, it was thought the Proterozoic unit would be dominated by the locally outcropping megacrystic to medium-grained syenogranite seen in outcrops proximal to Eavor-Deep. However, a more abundant metasediment component, along with significantly foliated, deeper more monzonitic granite (Figure 9) displaying an increase in metamorphic character, was found. A more comprehensive field study was completed while drilling the Proterozoic to better assess the heterogeneous rock relationships. The table below outlines the state mapped terrains that were focused on in both Arizona and New Mexico. Outcrop examples showed complex distribution of entrained or juxtaposed metasediments (Pinal schist), within and adjacent to both syenogranite and monzogranite, along with intersecting dikes.

Figure 10 Outcrop photos of the Proterozoic basement near Silver City New Mexico, showing the complex relationship between the monzogranite, syenogranite and metasediments.

Table 3 Maps describing the geologic formations targeted for the Proterozoic outcrop study.

Geologic map of Arizona: Arizona Geological Survey: Richard, S.M., Reynolds, S.J., Spencer, J.E., and Pearthree, P.A., 2000, Map 35, scale 1:1,000,000		**Geologic map of New Mexico: New Mexico Bureau of Geology and Mineral Resources: Scholle, P.A. 2003, Geologic Map, scale 1:500,000**	
1600-1800Ma) Early Proterozoic	Xm: Early Proterozoic Metasedimentary Rock (sandstone shale carbonate), Meta volcanic and Gneiss	**1600-1800Ma)**	Xs) Paleoproterozoic metasedimentary rocks pelitic schist, quartz muscovite schist, immature quartzite, and subordinate amphibolite
1600-1800Ma) Paleoproterozoic	Xg: Granite characterized by steep NE striking foliation	**1660-1650Ma) Paleoproterozoic**	Xg) Variably foliated granitic plutonic rocks and granitic gneisses
		Not well constrained	Yi) Mesoproterozoic Mafic dikes
1400-1450Ma) Mesoproterozoic	Yg: Porphyritic biotite granite with large microcline phenocrysts, local fine-grained border phases and aplite, forming large plutons.	**1450-1350Ma) Mesoproterozoic**	Yg) Mesoproterozoic megacrystic granitic plutonic rocks, more weakly foliated, except at margins

Within the borehole, the upper portion of the Proterozoic was dominated by syenogranite (Figure 11), however metasediments of the Pinal schist (figure 12), and the metamorphosed monzogranite (figure 13) became more frequently intercalated at depth.

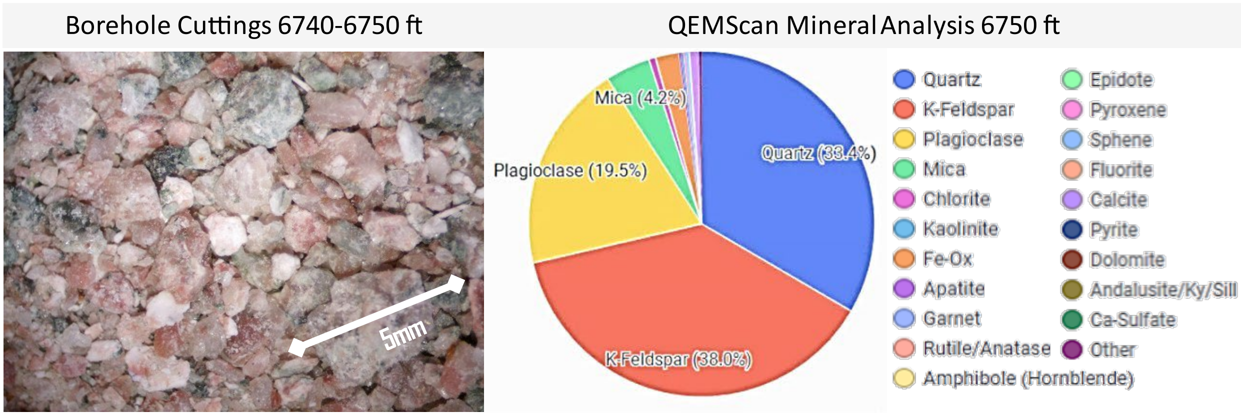

Figure 11 Sample from 6,750 ft Depth, syenogranite cutting photo (left), QEMScan mineralogy percent (right).

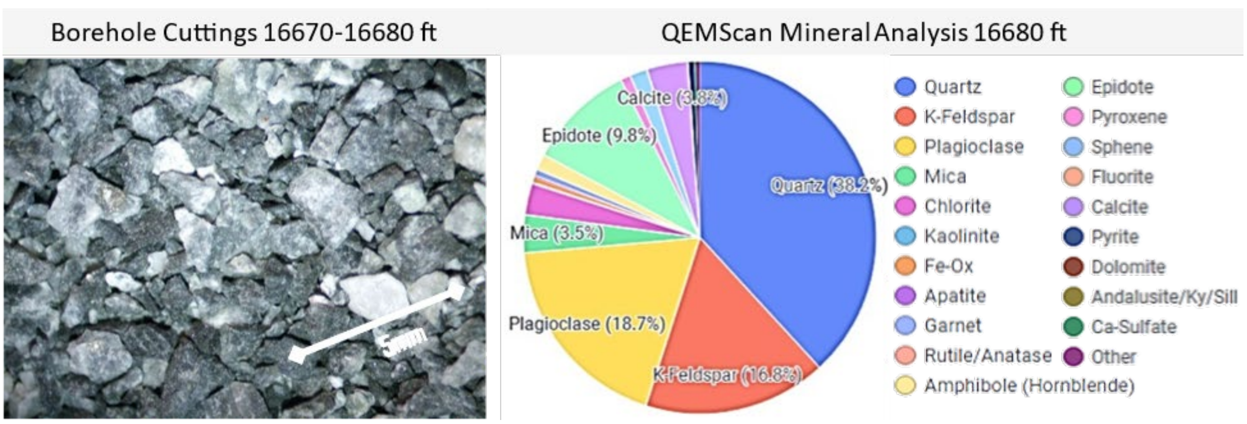

Figure 12 Sample from 16,680 ft Depth, quartz-rich metasediment cutting photos (left), QEMScan mineralogy percent (right)

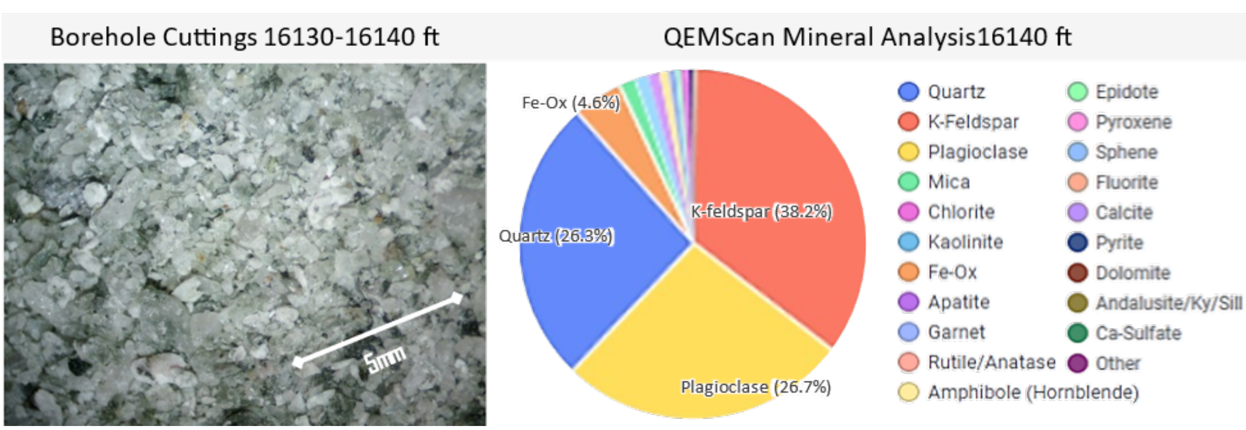

Figure 13 Sample from 16,140 ft Depth, monzogranite cutting photo (left), QEMScan mineralogy percent (right)

The increase in foliation intensity of the monzogranite and metasediment bed intersections, deeper in the borehole, provided complexity in drilling. Quick transitions between each rock type, with different rock physical parameters such as hardness, provided challenges in maintaining optimized drilling parameters and achieving longer bit life. Viewing the outcrop provided a useful analogue for understanding the complexity in rock fabric, rock type, and distribution, which helped interpret some of the rock bit interactions that were seen during drilling.

Given the representations of the Proterozoic seen in outcrop, along with the deep borehole cuttings and previously interpreted data, one possible Proterozoic geomodel is discussed below. With only Eavor-Deep borehole for deep cuttings data, limited deep geophysical imaging, and no age dating, or thin section work on the cuttings, there are many possible and viable interpretations.

Potential Proterozoic history:

- In the Paleoproterozoic, marine sediments were deposited in a back-arc basin and subsequently were intruded by Monzogranitic plutonism likely also in the Paleoproterozoic.
- Following this, extensive compression, folding, and metamorphism associated with the Mazatzal orogeny formed steep NE trending foliation fabric.
- During the Mesoproterozoic, mafic dike intrusions and syenogranitic (Porphyritic biotite granite with large microcline phenocrysts) plutons the Paleoproterozoic strata.
- The entire package was subjected to the Grenville orogeny causing weaker foliations to develop, in the syenogranite, and intensifying the already developed foliation in the Paleoproterozoic package.
- Following this event, there was ongoing erosion prior to deposition of the Paleozoic strata, starting with the Bliss formation in the Cambrian.

The diagram below illustrates the recent stratigraphy and current interpretation of the Animas Valley fault system and its relationship to the Proterozoic to recent rock packages as intersected by the Eavor-Deep well. This is one possible model for the area which can be more refined by further incorporating the geophysical surveys with the new borehole log and cutting data. Additionally, thin section and age dating from the cuttings may provide more details on rock fabric, replacement history and relative timing that could impact the interpretation.

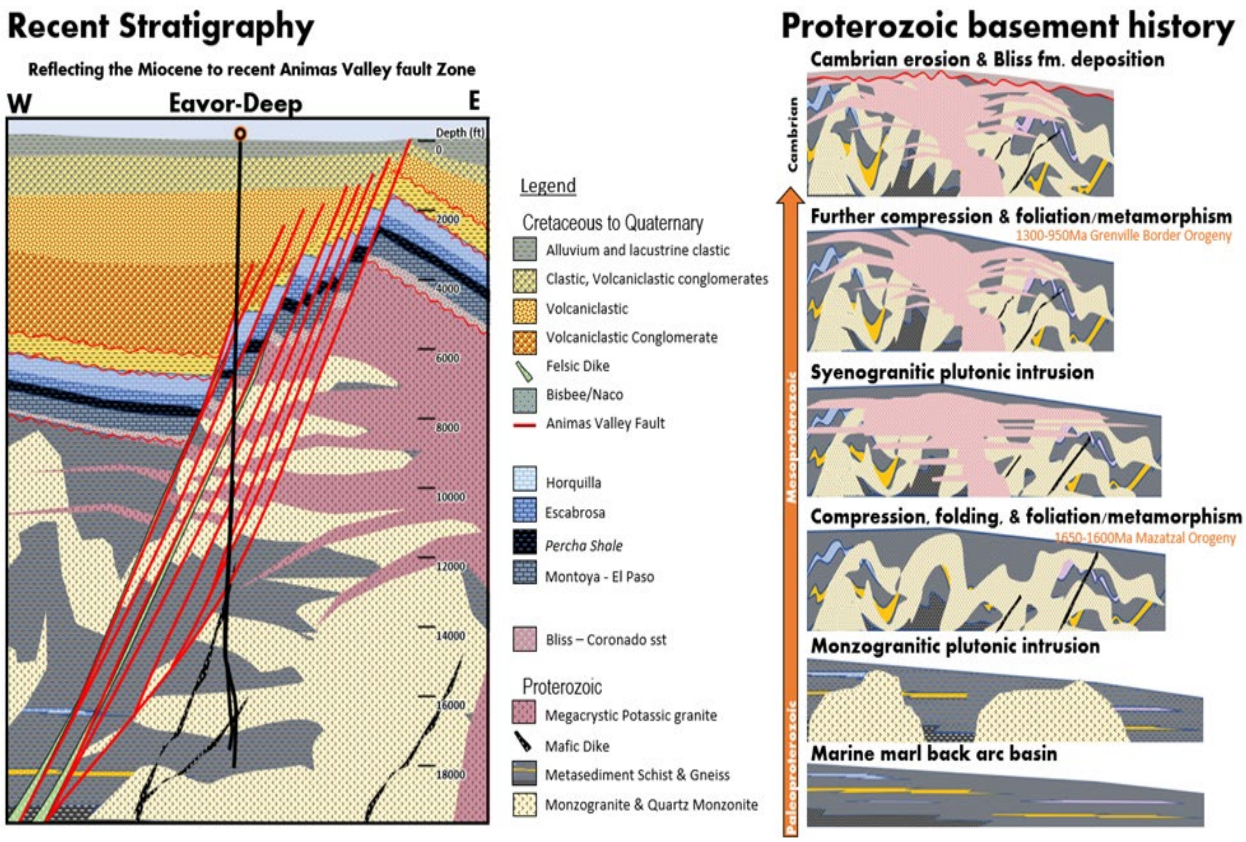

Figure 14 Possible geologic concept model for the Proterozoic geology penetrated by Eavor-Deep

5. Conclusions

Uncertainty modelling is useful for providing a distribution of possible realizations for:

- Generating reasonable uncertainty in a geologic prognosis for a deep (18,000 feet TVD) hole in a region where the next deepest well is 7,000’ and available historic reflection seismic data provides limited utility for stratigraphic and structural interpretations below roughly 4,500 ft.
- Providing guidance on casing decisions to isolate unstable formations and potentially permeable fault systems.
- Understanding the likelihood of intersecting or omitting certain formations, or faults.
- Understanding the uncertainty in the structural interpretation once constrained by geostatistical methods tied to control data points.

The field study was critical in viewing the heterogeneity, rock type relationships, and fabric of the Proterozoic rock to generate a conceptual model of what the geology may look like in the deep subsurface. Seeing the rock fabric in the outcrop can help to understand bit pull/push and better quantify the differences in the physical rock properties that drive bit and bottom hole assembly selection. Overall, the combination of uncertainty modelling and field assessment enabled a successful borehole design and conceptual model for an underexplored Proterozoic section below New Mexico.

Further work is required to refine the conceptual geomodel of the Proterozoic in the area, including thin sections analysis, age dating, and further geophysical study integration. The Eavor-Deep demonstration borehole provides a unique, first look at the heterogeneity of the deep Proterozoic underlying southwest New Mexico.

Acknowledgement

The Eavor-Deep project involved a great deal of collaboration and contribution from many, specific to the geologic prognosis, uncertainty modelling and field work, I would like to give thanks to the following people and organizations:

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- Stephen Longfield at Eavor Inc. for uncertainty modeling contributions

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