The use of Airborne EM to investigate coastal carbonate aquifer, seawater intrusions and sustainable borefield yield at Exmouth, Western Australia

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SUMMARY

Exmouth, a regional centre located 1260km north of Perth, Western Australia relies entirely on groundwater for its water supply. Its borefield extracts groundwater from an unconfined limestone aquifer within the Cape Range Group. Groundwater flows easterly from Cape Range into Exmouth Gulf where it discharges above a saline wedge at the base of the aquifer. The current borefield extraction has insufficient capacity to meet increased water demand from population growth and tourists during holiday periods.

In 2016-2017, Water Corporation decided to investigate options for improving borefield production from the existing infrastructure. This study comprised an airborne electromagnetic (AEM) survey, a desktop review, 3D hydrogeological modelling and pumping tests.

The AEM survey and new hydrogeological modelling have established a clear relationship between the extent of the saltwater interface and the location of karstic features. The AEM survey effectively mapped the saline water distribution. It identified existing bores in thicker lower salinity areas and away from the saline wedge. Twenty-four hour pumping tests of these bores were undertaken, producing flow rates much higher than the established normal production rates. Hydrogeological modelling indicated that these bores could accommodate substantial additional sustainable production. The AEM survey and study also identified bores in areas of higher conductivity and salinity where extraction rates should not be increased, or should be reduced.

Key words: Airborne Electromagnetics, Groundwater, borefield, saline water wedge, aquifer.

INTRODUCTION

Exmouth is located on the eastern side of the Cape Range Peninsula and is situated within the Exmouth Sub-Basin section of the Canning Basin. The town's main industries are tourism and fishing. The town's population can grow significantly during peak holiday periods, resulting in daily water usage increasing from an average daily rate of 2575m^3 up to 2982m^3. The current groundwater extractions and allocations meet the town's annual requirements. During these peak holiday usage periods, additional supply is extracted from distant bores that are not connected to mains power. Management of the town water supply is further complicated by the groundwater extraction being from two separate subareas within the same connected aquifer.

The AEM survey was designed to increase the understanding of the aquifer; in particular to identify sites where additional groundwater abstraction would be possible. The information was also used in modelling of the groundwater resource, improving understanding of overall groundwater flows. Fresh groundwater sits above a saline wedge that occurs at variable depth from surface. The saline wedge is expected to be very close to surface at the coast, with its depth increasing with distance from the coast (WRC, 2000). Airborne Electromagnetics (AEM) is an ideal tool for mapping the salt water interface because of the high conductivity contrasts between fresh and saline water. The SkyTEM helicopter system was chosen because it is well suited to hydrogeological investigations, having been specify designed for this purpose. Conductivity-depth inversions are well calibrated and understood for this system and ground water mapping applications.

No significant geophysical ground water investigations have been undertaken previously in the Exmouth and the Cape Range area but there have been numerous investigations of the hydrology and hydrogeology of region. . Petroleum exploration has been active since the 1950's. Comprehensive Town Water Supply drilling is recorded from 1972-3, starting with Forth (1972) estimating ground water resources and postulating that fresh groundwater occurred in a wedge tapering out seawards. Further exploratory drilling by the Water Authority (Martin, 1990) provided more detailed information, showing that inland from the coastal plain, fresh groundwater extended to more than 100m below sea level in rocks that were previously considered impermeable.

Cape Range is formed by a structurally complex anticline, a result of inversions along the Learmonth Fault (Allan, 1991). It is made up of two main formations; the Cape Range Group, and the Birdrong Sandstone (WRC, 2000). The Cape Range Group on the eastern side of the anticline consists of three conformable formations; i.e. Trealla Limestone, Tulki Limestone and Mandu Limestone . Drilling intersected thin bands of clay or clayey limestone in most boreholes, with core loss interpreted as zones of more karstic limestone. All three formations are interpreted to be hydraulically connected and are grouped together as a single unconfined limestone aquifer. Based on the two drill holes close to town, it had been assumed that the saline incursion reached approximate 5km inland from the coast. However, the AEM survey showed that the saline incursion was less extensive in the southern part of the survey area.

AEM SURVEY, PUMP TESTING AND MODELLING METHODOLOGY

The AEM (SkyTEM^{TM}) survey was completed in August, 2016, consisting of 476.4 line kilometres of flying immediately around the town of Exmouth. The survey flight plan (Figure 1) shows the unconventional survey flight path, with detailed, 150m spaced flight lines flown sub parallel to the coast (015^{O} – 195^{O}) in the priority area of interest (over the borefield) and 500m spaced flight lines perpendicular to the coast (105^{O} - 285^{O}). Other line directions and gaps are related to the location of the town and associated infrastructure, a military radar site and flying time restrictions in the vicinity of the military radar.

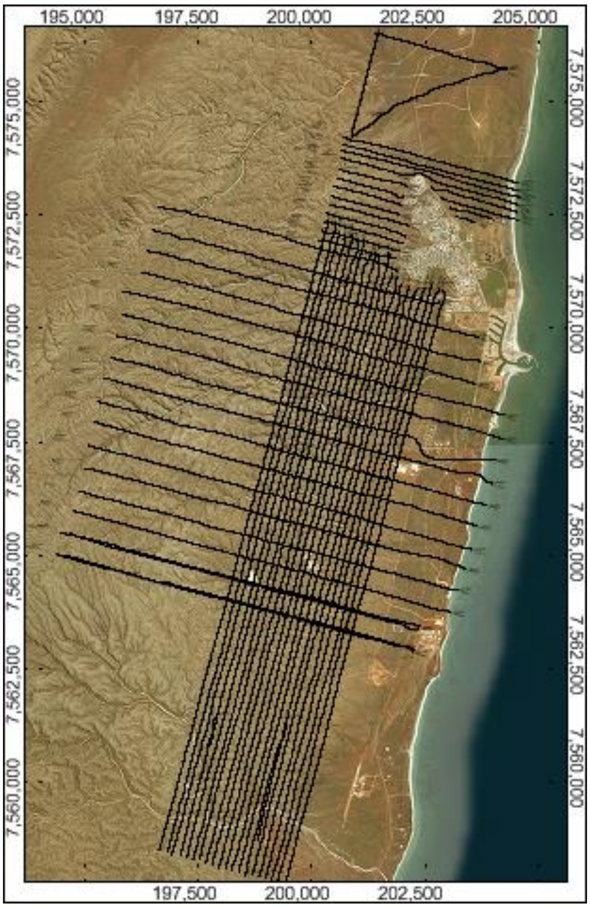

Figure 1: SkyTEM Flight path on aerial photography.

SkyTEM is a time domain helicopter borne electromagnetic system, originally designed for hydro-geophysical and environmental investigations by the Danish Ministry of Environment and scientists at the University of Aarhus.

The SkyTEM data have been modelled with the AarhusInv program (Auken et al., 2015) using the Aarhus Workbench LCI algorithm (Auken et al. 2005; Auken et al. 2002). The AEM readings were simultaneously being inverted using 1-D models (Kirkegaard and Auken, 2015). Each reading yields a separate laterally constrained layered model. The result of the LCI inversion is a quasi-2D model section that varies smoothly along the profile, yielding a sub horizontal conductivity distribution.

In addition to the 30 layer LCI smooth inversion, the AEM data have been modelled using the spatially constrained inversion (SCI), (Viezzoli et al., 2008). In the SCI algorithm a group of time domain EM (TEM) soundings are inverted simultaneously producing a quasi-3D model. The SCI code was run in five-layer model mode, in which the data are inverted for layer thickness and conductivity, using the 30 layer LCI smooth model to provide initial constraints to the starting model.

The data and inversions of the Exmouth survey are of good quality despite the close proximity to the military's very low frequency (VLF) radio transmitter and radar stations. These were expected to be significant sources of noise.

Subsequent to the AEM surveying, pump testing of 10 bores was undertaken. Common pump testing practice uses high abstraction rates to stress the aquifer and cause a significant drawdown. The rates of abstraction were limited due to the karstic nature of the limestone and the uncertainty in the location of the salt water interface. The water couldn't be discharged into the environment, because the karstic nature of the limestone could result in rapidly recharging of the water, so it was feed back into the reticulated scheme. The volumes of abstracted water were approximately double the standard production at between 250-300m$^{3/}$day. Salinity was constantly monitored.

Aquifer modelling was undertaken using Leapfrog ^{Tm} 3D Modelling Software utilising bore logs completed during the original drilling of the bores. The bore logs are interpreted into separate lithologies and Leapfrog interpolates these lithologies to create a 3D model of the geology; the more accurate and thorough the bore logs, the higher the potential for a more accurate/representative 3D model. In the Exmouth case the quality of bore logs varied as the drilling information used spanned 30 years. While the quality of logging was variable, the quantity of bores drilled over this time meant enough high quality bore logs were present to create a reasonable 3D representation of the aquifer system using the Leapfrog^{TM} software package.

RESULTS

The airborne EM survey was very successful in locating and defining the saline water wedge and interface, which is the highest conductivity feature in the survey. The lateral extent of the saline wedge (red & yellow colours) has been interpreted from the LCIs and the SCIs in Figure 2. In the north of the survey area, near the town centre the seawater incursion extends approximately 5.6 km inland from the coast and is approximately 3.6 km from the coast in the southern part of the survey. Figure 3 shows a comparison of LCI and SCI inversion. The LCI's have primarily been used to estimate depths and conductivities as the five-layer model of the SCIs has sharp, possibly artificial boundaries between layers. These appear to be less well correlated with drilling, and are predominantly shallower than expected. The lateral extents of the saline wedge are well correlated between the LCI's and SCI's. This adds confidence to the interpretation.

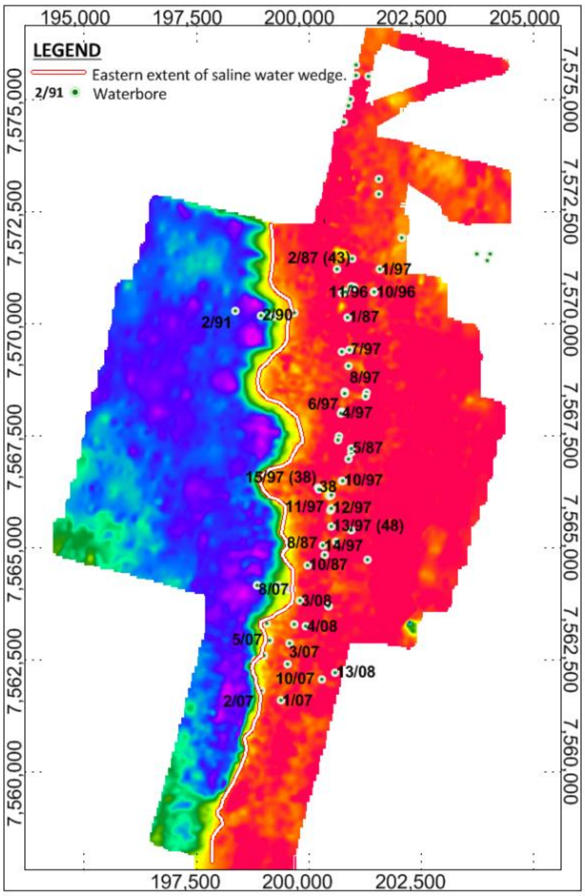

Figure 2: Interpreted edge of Seawater interface on -43m (AHD) LCI.

The most obvious feature in the survey, i.e. the strongest modelled conductivities is the saline aquifer. The maximum conductivities are 2100 mS/m in the LCI's. However, lower values of approximately 250 mS/m from near the edge of the saline wedge have been used for estimating the depth and location of the transition to the saline aquifer, (Figure 3). This value could be more representative of a mixed salinity zone, or be a product of the smoothly changing inversion. As expected the high conductivity saline aquifer is close to sea level (0m AHD) close to the coast and increases in depth towards the west to west-north-west, but this increase is not uniform. On Line 201201 (Figure 3) the red high conductivity layer is easily interpretable as the saline water interface. It can be seen that the highly conductive red unit is shallower around the drill holes 12/97, and 40. This zone of increased conductivity is also highlighted in plan view (Figure 5). This shallower high conductivity zone is interpreted as reduced depth to the saline water interface, increased salinity, or a combination these two factors. The zone of increased conductivity is seen in both the LCI's and the SCIs but the SCI sections are interpreted as being less reliable due to the high conductivity saline water zone extending above the top of the aquifer (0m AHD) when no increased salinity has been measured in the bore. This discrete area of increased salinity/reduced depth to saline water is located around 5 production bores which are in close proximity and is most likely caused by over extraction from these bores. This over extraction could have occurred well in the past, as the salinity change is often slow to recover. The increase conductivity could also be partially or totally related to higher clay content in the limestone. If this was the case it would also reduce the permeability and the prospectivity for increased extraction from these bores.

Interpreted LCI sections in Figure 3 show other features of interest, including resistive dry limestone, the depth to fresh water, areas of elevated clay content (within the limestones), and possible higher salinity zones or shallower saline water. These features have less obvious conductivity responses, but are able to be interpreted with other supporting information such as drilling.

Based on water level measurements made in August, 2016, the top of the fresh coastal carbonate aquifer is very close to sea levelwith depths ranging from 1.83 AHD (Hole 2/08) to -1.92 AHD (Hole 16/97). The top of the fresh aquifer is a challenging EM target as the conductivities are very similar to limestone with moderate amounts of clay. The top of the aquifer is well mapped by the existing drilling but is less certain outside this area.

The plan view of the distribution of elevated clay content units, and zones of thicker fresh water is shown in Figure 5. The main areas for interest are areas west of the saline wedge or in thicker zones of fresh water. There are two discrete areas of lower conductivity interpreted as thicker zones of fresh water (Figure 5). There is an additional zone in the south of the survey adjacent to the western extent of the saline wedge that is also interpreted as a thicker zone of fresh water. These zones of lower conductivity have been interpreted as lower salinity and/or thicker fresh water, but could also be related to lower clay content.

Pump testing was undertaken on 10 production bores identified by the AEM survey to potentially be in areas either west of the identified salt water extent or in areas identified as having thicker zones of fresh water. From the ten bores that were involved in the pumping test, only two showed any significant drawdown after 24hours. Maximum drawdown was reached within these two bores approximately half way through the pumping test and remained steady for the reminder of the test, with no change in salinity values. It is believed that these drawdown results indicate they are either screened within a "tight" or less cavernous section of limestone within the aquifer, or have not been drilled deep enough within the thicker fresh water zones identified by the AEM results.

For the 8 remaining bores maximum drawdown after 24 hours varied between 0.02 and 0.44m, with no change in salinity. It is believed these minimal drawdown values indicate the bores are screened within a more cavernous section of the limestone aquifer, related to the thicker fresh water zones identified by the AEM survey.

The 3D aquifer model (Figure 6) was completed independent of the results of the AEM survey so that these results independent results could be compared and contrasted. The main aim was to determine if the thicker fresh water zones and the extent of the saltwater intrusion interpreted from the AEM survey correlate with the 3D model. The 3D aquifer modelling and the AEM showed a good correlation between the thicker groundwater areas identified from the AEM survey and areas within the 3D model where the weathered limestone was either absent or had pinched out in areas in close proximity to the cavernous limestone.

CONCLUSIONS

The SkyTEM survey planning and flying was complicated by the close proximity of military radar and VLF stations, but the final data was of high quality. The AEM survey has effectively mapped the location of saline groundwater. The lateral extent of the saline groundwater is variable and extends inland between 5.6 km in the north and 3.6 km in the south of the survey area. Potential thicker zones of fresh water have been interpreted. There are significant numbers of bores that are either west of the saline groundwater wedge and/or within thicker fresh water zones interpreted from the AEM. These bores are all considered to be good targets for increased ground water production.

Limited 3D aquifer modelling concluded that the zones of thicker fresh water interpreted from the AEM correlate well with locations where the weathered limestone was either absent or had pinched out in areas in close proximity to the cavernous limestone. This is interpreted as the reason for the thicker fresh water zones.

Pump testing was undertaken on 10 bores from these thicker freshwater target areas and or west of the saline groundwater wedge. The results indicated 8 of the 10 bores have the potential to sustainably abstract increased volumes of water. Approximately 280kl/day extra supply could be sourced from bores believed to be screened in areas identified by the AEM survey as having thicker fresh water zones, as well as a further 350kl/day available from 3 of the 4 bores pump tested which were identified as being west of the furthest extent of the saltwater intrusion zone.

A discrete area of increased conductivity centred on 5 production bores locationxxx is interpreted as a zone of increased salinity and/or reduced depth to the saline water interface. As such these bores are recommended for careful monitoring, but are not recommended for increased ground water abstraction.

The combination of the AEM, pump testing and modelling has facilitated increases in production from existing bores, reducing the need for additional exploration drilling in the short term. In the future as water needs increase, good, deeper target areas have been identified. These could provide high water production with lower risk of increased salinity. Many of these targets are at or close to existing pipelines, which will significantly reduce the cost of connection new bores to the reticulated scheme.

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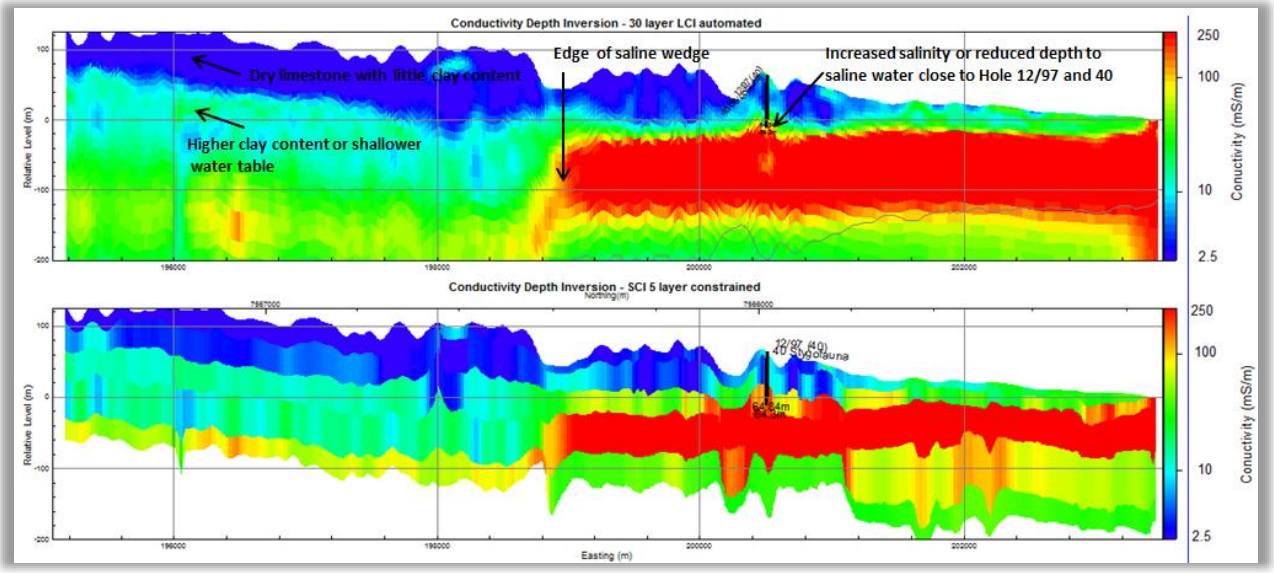

Figure 3. Line 201201 LCI and SCI section. Thick red zone represents the saline wedge.

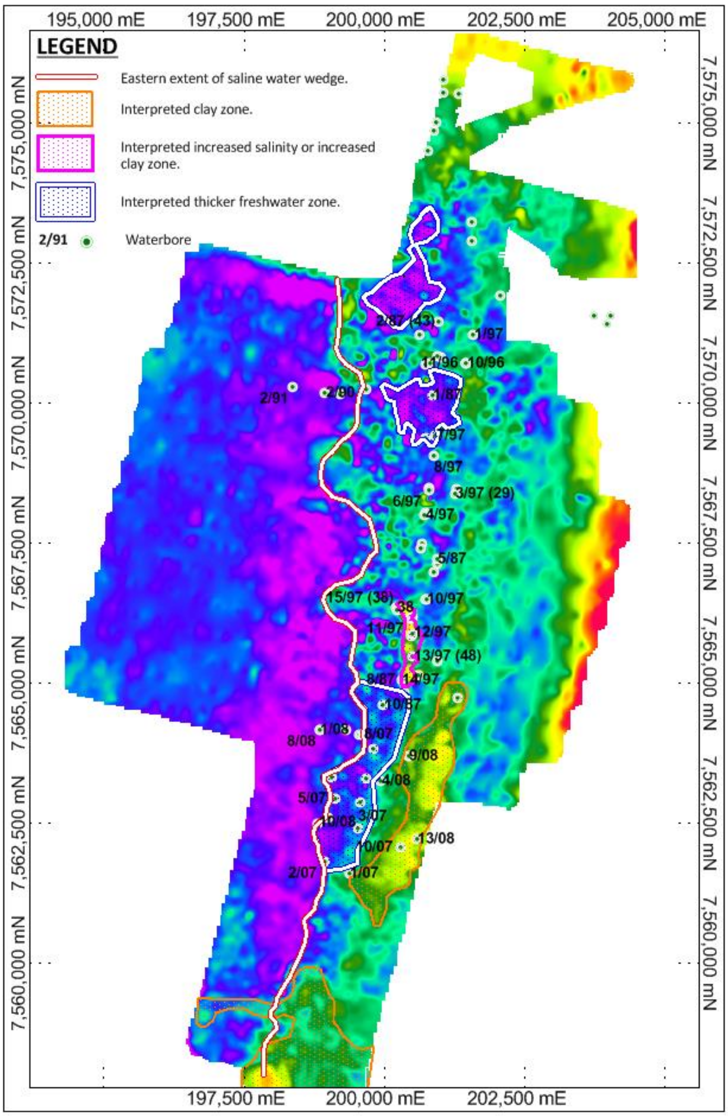

Figure 5: LC1 -7m AHD (log pseudo colour image) with AEM interpreted zones.

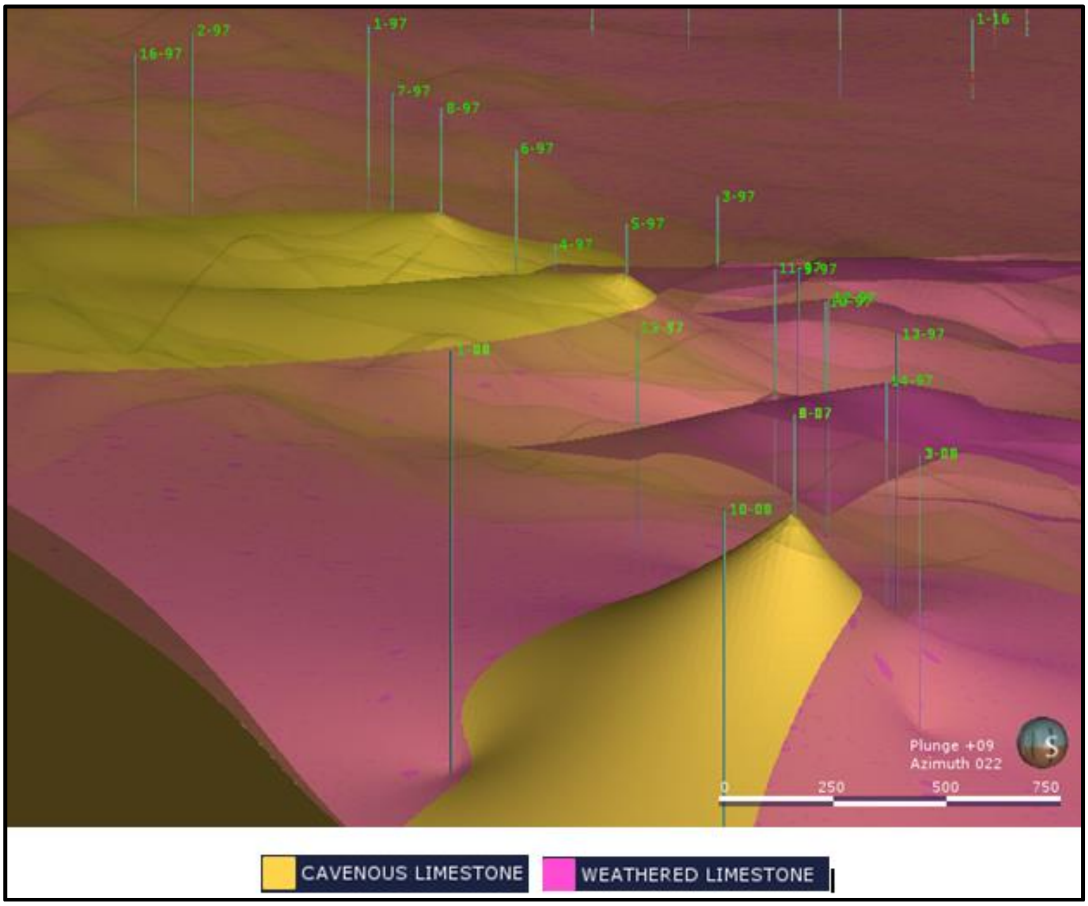

Figure 6: Oblique section of 3d model.