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Modern GIS Geodatabase in Geotechnical, Geophysical and Geological Analyses and Applications

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In 1989, Qatar set in place a strategy and vision for the world's first integrated national GIS. Today, the implementation of that vision plays a major role in integrating diverse multi-scale, multi-disciplinary spatial data from geological rock samples to multi-spectral satellite imagery for use in solving complex geological, geophysical, geotechnical and environmental problems. Detailed knowledge of Qatar's surface and near-surface geology is key to a better understanding in geotechnical, geophysical and geological work. All three disciplines depend on reliable information about the surface and each discipline provides the others with vital near-surface information. GIS provides the integration and window into the data for enhanced analysis.

Figure A – GIS-based surface geology polygons of Qatar with transparent display of an Eocene formation to show underlying features of IKONOS satellite image (used with permission from Qatar's CGIS, UPDA)

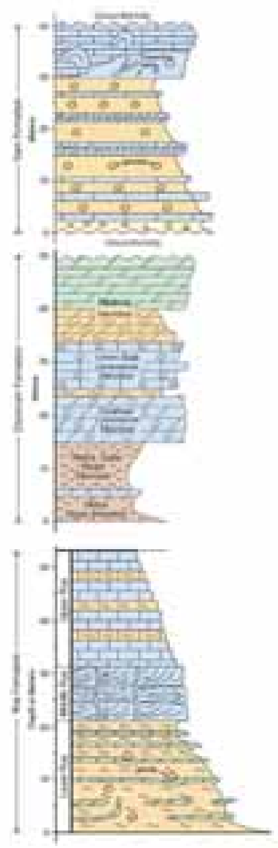


Figure B – Schematic stratigraphic column of the near surface geology of Qatar.

Figure C –Aeolian Sand Dunes of Khor Al-Adaid

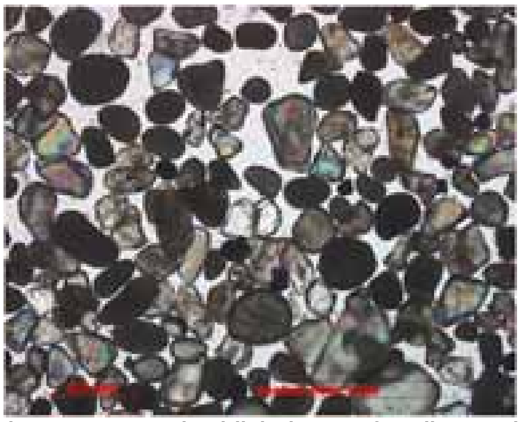


Figure D –Transmitted light image of aeolian sand. Translucent grains are quartz, opaque grains are carbonate. All grains show characteristic aeolian rounding and good sorting (0.2 mm in diameter)

GIS data from all of Qatar's ministries can be incorporated into a single analysis, including soil type, land use, surface geology, structure, topographic digital elevation model (DEM), satellite imagery, roads and cultural data. Through GIS, these data are rapidly incorporated with proprietary data from borehole cores, seismic survey data, engineering facilities and infrastructure. The strengths of the ArcSDE geodatabase lie in three areas that are the topic of this paper. First, the power of integration of information from such disparate sources as surface mapping, borehole geotechnical data and satellite imagery. Second, GIS databases capture the source and quality of input datasets. Data from different sources differ in quality, structure, resolution, classification methods, projections and accuracy. GIS analytical tools resolve the differences between sources, producing the best possible data for analyses. Third, analytical methods are readily captured in the GIS metadata structure. Several examples presented here from Qatar illustrate the value of an integrated GIS in decision making for solving industrial, geotechnical, environmental and geological research problems.

Since 1990, industry initiatives (e.g. POSC) have set to improve data sharing and quality. Major advances have been made through GIS systems. Data are now georeferenced to a known datum and projection; vector and image data can be readily re-projected to any specified datum and projection. One major advance has been the incorporation of metadata in GIS.

Metadata is required to make the data useful. Metadata explains exactly the resolution, accuracy and data gatherer's intent. It represents a set of characteristics about the data that are normally not contained within the data itself. The use of metadata in the geodatabase ensures that all available defining information about the data is known. Details about sources, precision and format are captured. Quality assurance is an inherent property of the GIS database. Qatar's geodatabase includes Landsat, SPOT, Quickbird, IKONOS and aerial photography to 20cm resolution. It also includes digital elevation models and cultural data. Qatar Petroleum's geodatabase includes all oil and gas facilities (e.g. wells, pipelines), topography and geotechnical borehole data. Qatar's ArcSDE data server was designed for access to GIS data in any format and datum, and to use multiple database management systems concurrently. The geodatabase provides: high-performance; spatial integrity; management of extremely large data volumes; a common interface to database management systems; and support for industry data models.

Reconciling Between Data: Example from Updating the Geological Map of Qatar

Qatar's growing oil and gas industry has given rise to an unprecedented boom in building commercial and industrial infrastructure. Planning for growth with minimal environmental impact relies on an understanding of the existing ecological baseline. Qatar Petroleum is undertaking a re-evaluation of the surface geology and soils of Qatar. This project illustrates the power of a GIS database in reconciling between several types of historical data and the added value of integration. Three sources of surface geological data are available in Qatar: Cavalier-Salatt (1970) map [1] [2] largely based on surface mapping, Seltrust (1980) [3] based on aerial photo interpretation and some mapping, and a soil survey (2005) [4]. Sources were mapped in differing projections. The classification system and polygon outlines for each also differ. Comparison of the three sources within GIS illustrates the strengths and weaknesses of each dataset, together with areas where time-consuming field geological mapping verification are needed.

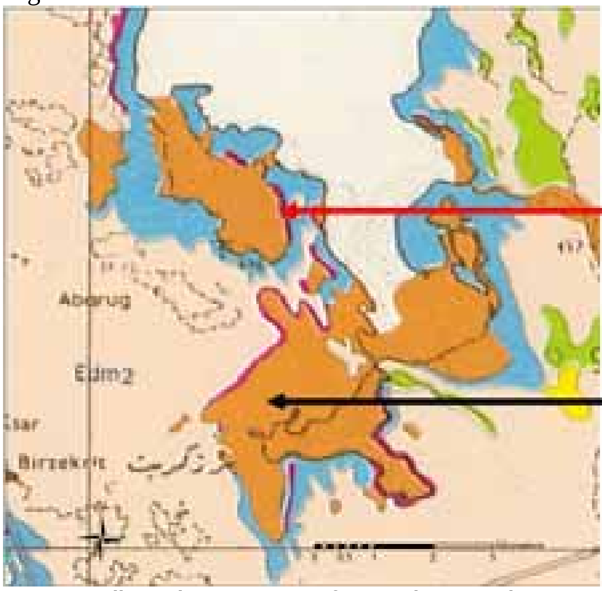


Figure 1A Cavelier-Salatt 1970 Georeferenced Scanned Paper Map From Extensive Field Geology Mapping

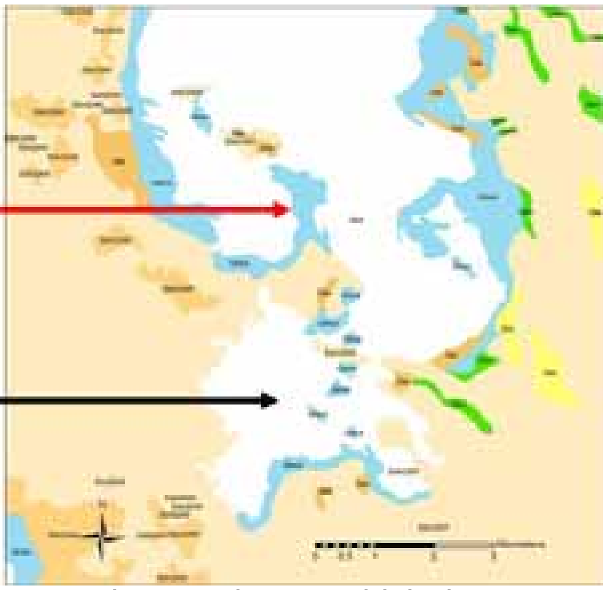


Figure 1B Seltrust 1980 Digital Polygon Map from Aerial Photo Interpretation

Figure 1C High-resolution 2008 Aerial Photography

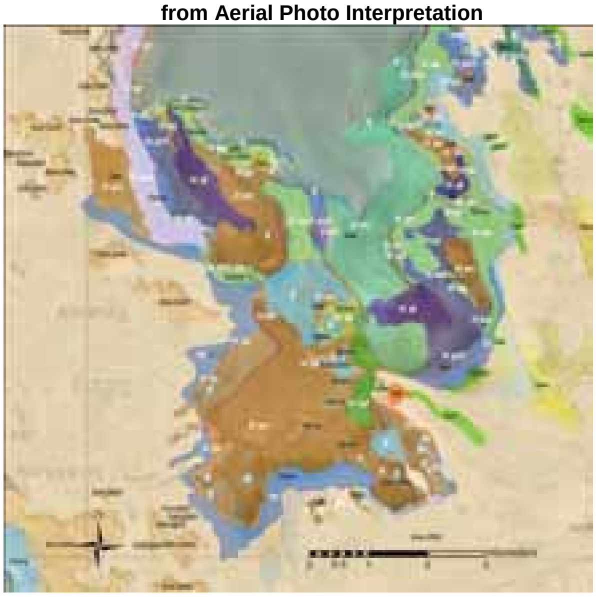


Figure 1D Overlay Comparison - 1970, 1980, 2008 Maps

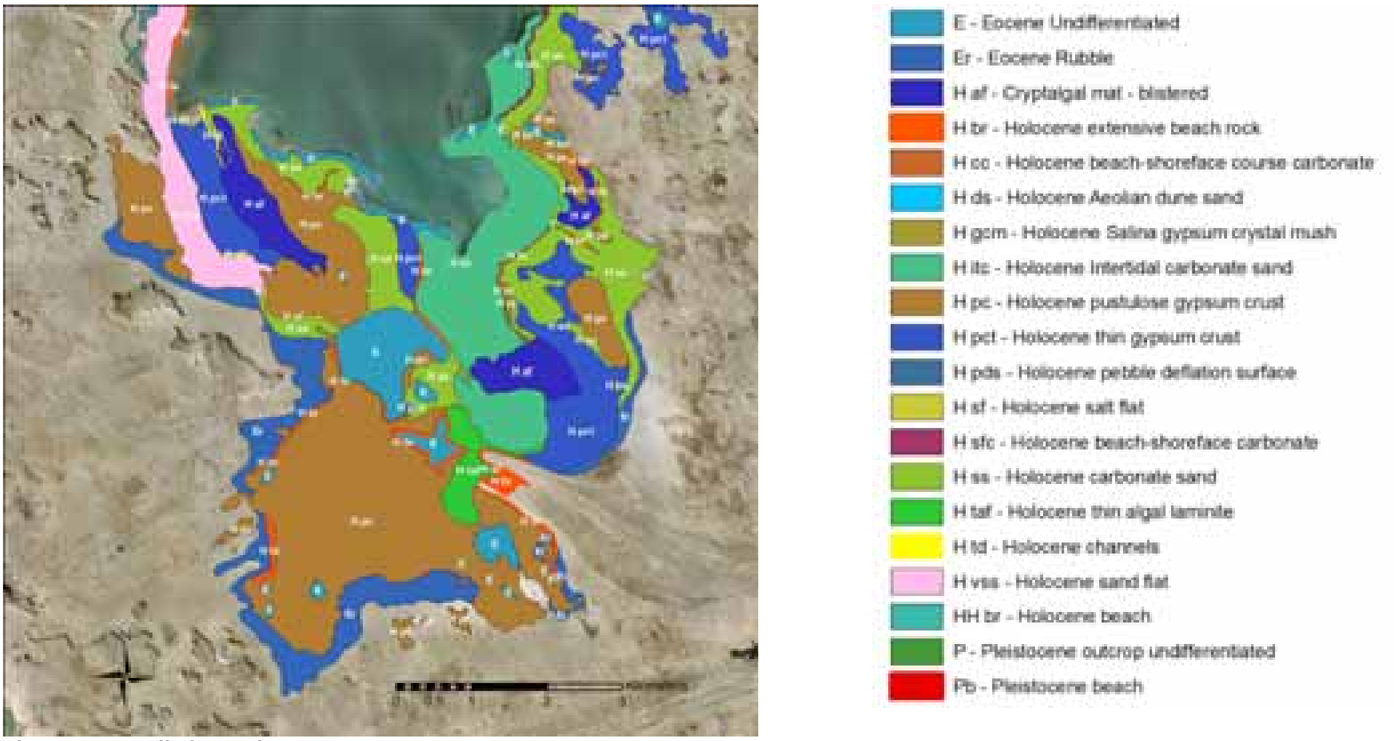


Figure 1E Detailed Mapping 2008

Figure 1 Comparison of existing data illustrates the problems and benefits of different sources of data in analyses.

- **A. Figure 1A shows part of the Lower (Northern) Dukhan Sabkha as mapped in 1970 from extensive field work. The extent of the sabkha is shown in orange and has an area of 14.5 square kilometres. Despite a map scale of 1:100,000, good detail can be seen of the Pleistocene calcareous sandstone beach rock (shown in red). No distinction was made of the Eocene-age Upper Damman formation (shown in light tan as Edm2).**
- **B. Figure 1B shows the same area as mapped in 1980 by Seltrust Engineering Ltd and currently held by Centre for GIS (UPDA) as digitized polygons. It is based on limited field work and with extensive use of photogeological interpretation of 1:36,000 scale aerial photographs (1977) by Hunting Geology and Geophysics Ltd. An extensive part of the sabkha mapped by Cavelier-Salatt in 1970 is missing (noted with a black arrow). In addition, the detail of the Pleistocene calcareous sandstone beach rocks is also missing (noted with a red arrow). Mapping included surface elevations that were not posted by Cavelier (1970) and sub-dividing of the Eocene Upper Damman into Edsm2SM (Simsima) and Edsm2AM (Abarug) dolomitic-limestone. On the original Seltrust 1980 paper map, dotted lines reflected confidence in surface geology polygon boundaries. In digitizing the paper map, the significance of the dotted lines is lost unless this is reflected in the metadata. This example illustrates the need for full metadata to be carried with the digital data.**
- **C. Figure 1C shows the same area in 2008 from a high-resolution (50 cm) aerial photograph acquired by Qatar Petroleum's Technical Directorate.**
- **D. Figure 1D shows how GIS provides the ability to overlay each of the maps in real-time even though all three are in different datums and projections. The scanned and georeferenced Cavelier 1970 paper map is in an historical now-unused 1948 datum and projection, the Seltrust map is in Qatar National Grid and the 2008 detailed mapping was obtained in WGS 84.**
- **E. Figure 1E shows a 'perfect solution' surface map from 1:10,000 scale mapping. The detail visible in 1C provided the template for 1:10,000 scale mapping and sample collection by geologists on the ground. Cavelier's extensive sabkha has been re-discovered as has the Pleistocene calcareous sandstone beach rock. Radiocarbon age-dating of samples has revealed beach rocks from a Holocene high-stand (>4,000 ybp) as well. Since digital mapping no longer has the detail constraints imposed by paper maps, GIS allows far greater accuracy as well as superior detail through the use of abundant mapping unit facies. The use of GIS techniques such as image georeferencing, image transformation, geoprocessing and transparency allow a comparison of the mapping.**

Value of GIS Integration: Examples in Research of Recent Holocene and Past Sea-Level Change

The ability to integrate such disparate data as radiocarbon age-dating, surface geology and geophysics illustrate the analytical capabilities of GIS. As part of a geological research effort, Qatar Petroleum has incorporated age data from surface sediments into the geodatabase. This analysis reveals an elevated terrace, approximately 2 meters above present day sea level, dating between 4000 to 6000 years before present. A combination of GIS satellite imagery, the DEM and age-dating indicate the presence of a previously undocumented event in the Holocene sea level history of Qatar. GIS analysis provides the basis for geological research into processes that aid the understanding of coastal processes and the development of analogues for the interpretation of ancient oil and gas bearing rocks. Holocene coastal and sabkha deposits of Qatar illustrate depositional trends that aid in the interpretation of ancient, evaporate-carbonate reservoir sequences. Recent data provide new insights into evaporate distribution, facies and stacking patterns of sediments deposited during the Holocene sea level rise. Comparison of coastal deposits from different regions of Qatar formed during the Holocene sea level rise reveals new insights into characterization of ancient rocks.

Figure 1F View from southeast of area illustrated in Figure 1A-E. The image from Figure IC is draped over a digital elevation model (DEM) created from digital elevation values in the GIS geodatabase. The subsequent 3D model is viewed from the South-East towards the North-West. An Eocene ridge is in the foreground.

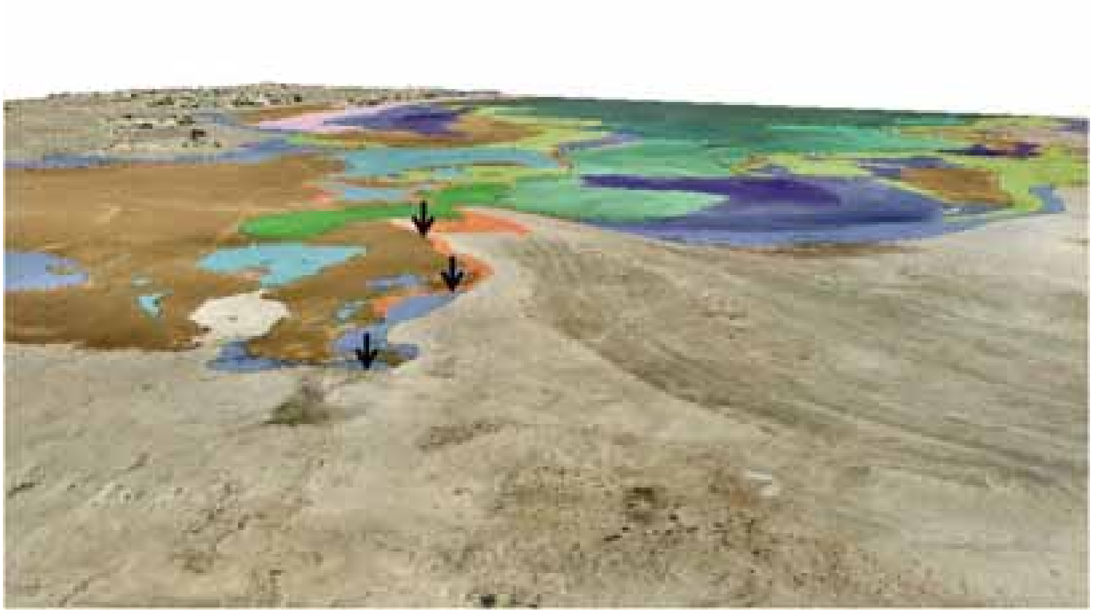


Figure 1G This shows the integration of radiocarbon dating, the new surface geology mapping and the 2008 aerial photography image from Figure IC with the digital elevation model (DEM). Holocene high-stand beach rocks can be seen in red near the centre foreground (see arrows).

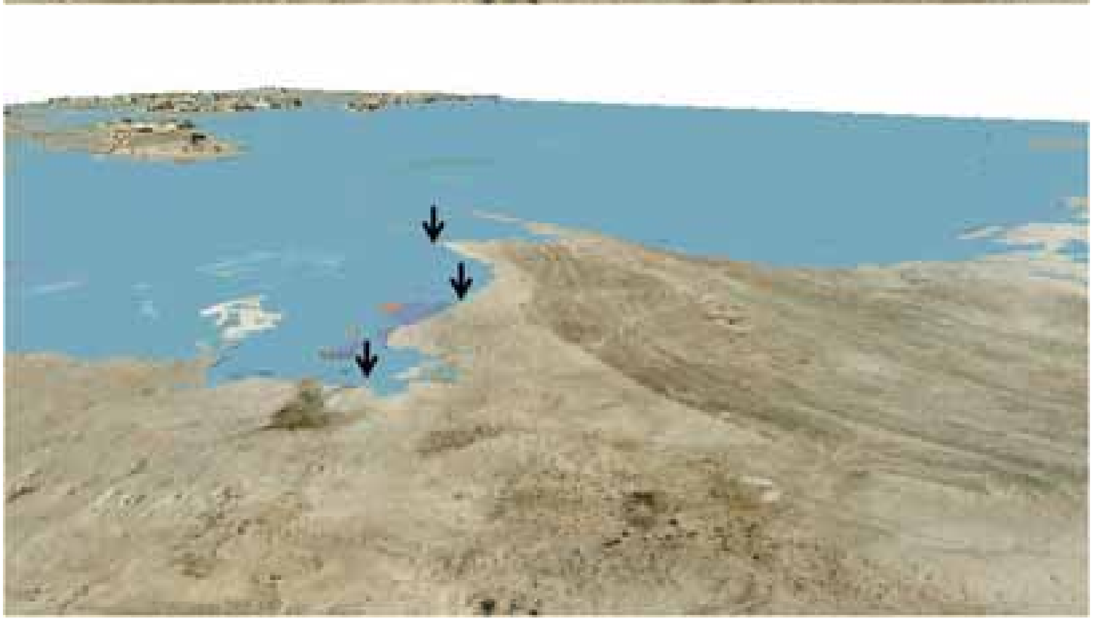


Figure 1H This shows integration of all of the above in Figure 1G together with a flat sea-level surface which can be projected at any height below or above current sea level. The level shown here is 2 metres above current sea-level and highlights the Holocene high-stand beach as it appeared 4,000 to 6,000 years ago.

The ability of GIS to integrate bathymetry, surface topography, satellite imagery, radiocarbon age-dating and surface features provides visualization of recent and historical sea-level changes for Qatar and the Gulf.

Figure 1J: Present. Sea-level shown as red line.

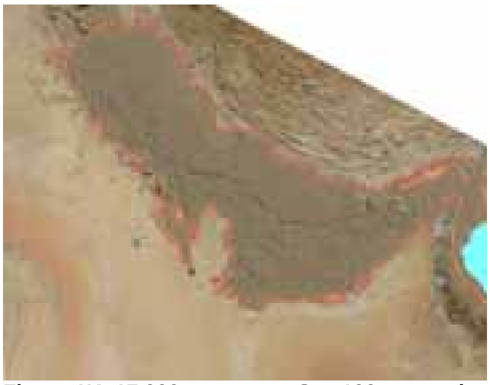


Figure 1K: 17,000 years ago. Sea 100 metres lower. Dry land between Qatar and Iran.

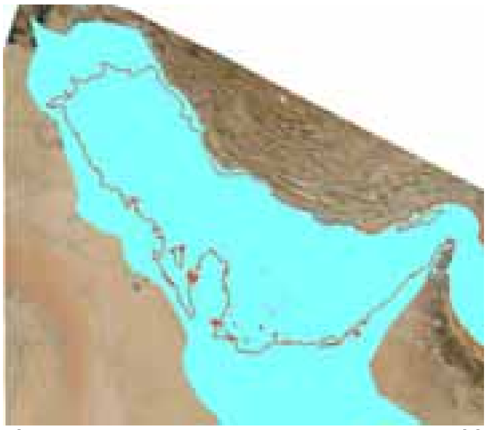


Figure 1L: 240,000 years ago.Sea 100 metres higher.

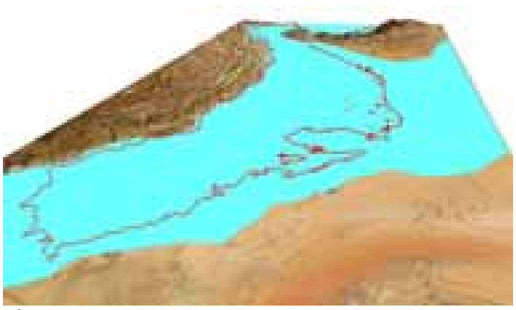
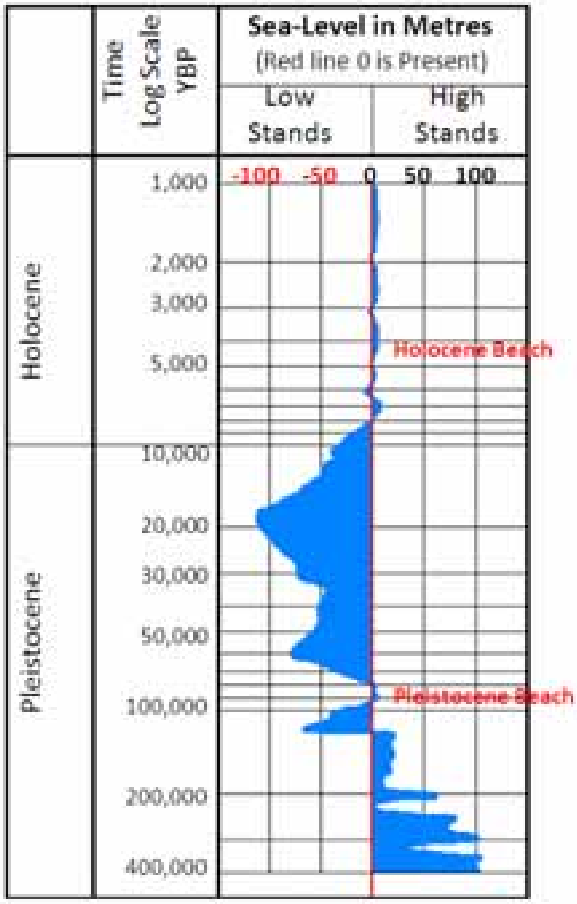


Figure 1M: 240,000 years ago. Sea 100 metres higher. 3D perspective GIS view of Qatar completely under water.



Sea-level based on Puls (2008), Haq (2003), Fairbridge (1961) and Weijermars

Figure 1N: Qatar coastline as it appeared 4,000 years ago. Red line is current sea-level. GIS mapping through DEM data and interpretation of radiocarbon age-dated rocks.

The distribution of surface sediment types can be further enhanced by image processing of multi-spectral satellite data such as supervised classification or principal component analysis of short-wave infrared bands. Analysis reveals sediments masked by seasonal changes in surface moisture and salt content. The map is enhanced by GIS analysis combined with existing data.

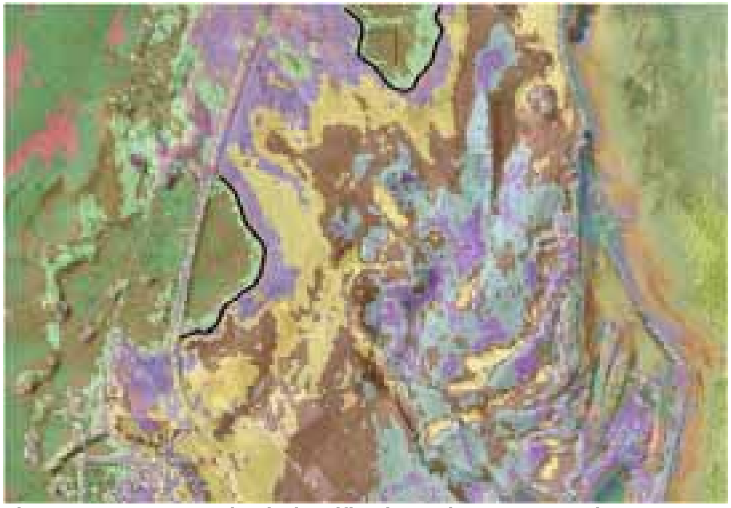


Figure 2A – Unsupervised Classification using SWIR Bands

Figure 2B - GIS in Geophysical Data Planning

Figure 2A shows an unsupervised classification of three multi-spectral SWIR bands of the surface soils and geology of Qatar's Mesaieed area. The division between the light green and light purple pixels shown as black lines marks the maximum flooding extent. Figure 2B clearly allows distinction between vegetation stabilized sand and sheet sands. It also shows how GIS data is used in planning geophysical seismic surveys to avoid hazards and in ensuring the correct coordinates of wells in interpretation. The red dot highlights a spatial error from the actual well coordinates as indicated by the arrow. This mismatch is rapidly identified through the visual approach provided by GIS and the technique is used by Qatar Petroleum to validate historical well location coordinates.

GIS in Geophysical Planning and Analysis

Qatar Petroleum is planning one of the largest onshore 3D seismic surveys world-wide using GIS. The planned location of every shot point and receiver location is based on GIS images and vector information. The value of the GIS system is seen in optimizing operational efficiency, hazard/obstacle identification, ensuring operations safety and minimizing environmental impact. Seismic vibrator ground coupling is important. Sand and flat hard surfaces are good for sound transmission - there is a need to avoid rocky surfaces. Access is vital, together with the need to avoid underground pipes and obstacles by two at least metres. Use of GIS in integrating surface geology and topography assists in modelling near-surface velocities vital to seismic processing. Figure 2B shows typical hazards to be avoided when planning shot point and receiver locations. Figure 2B also shows how fully georeferenced high-resolution satellite or aerial photograph imagery can be used to check well locations before they are used in geological interpretation packages. The red dot shows where a well has been misplaced either through incorrect keying in of location coordinates, the use of a provisional well location, or where a well has been surveyed in a different datum or projection.

GIS in Geological Modelling of Surface Processes

Seventeen thousand (17,000) years before present, sea-level is predicted to have been approximately 120 metres lower than the present sea-level. The whole of the Gulf area, including the Hormuz Strait, was dry. Aeolian sand was transported across the Gulf area, including over Qatar. Approximately 8,000 years ago, the Gulf of Salwa flooded, cutting the peninsula off from the regional sand supply. Since this time, dune sands have been moving from northeast to southwest. Remnants of these dune fields are still preserved on the eastern coast, along Khor Al Adaid, a candidate UNESCO World Heritage site. This unique geological setting has been selected to illustrate the value of GIS data in coastal research and conservation.

The 50 km long coast consists of sabkhas overlain by spectacular aeolian sand dunes and shown in figure C on page 1. Time lapse image comparison through GIS and age-dating reveals precise rates of sand dune movement. GIS allows quantification of dune sand volumes, and hence available resources for commercial activities such as cement production. Sand dunes move at different rates largely depending on their surface area and volume of sand; the larger the dune, the slower the movement. Assuming uniform dune movement rates over time, GIS data provide the basis for forward modelling and prediction of when the dunes will fill the narrow strait separating Qatar and Saudi Arabia. Closing of the strait will create an evaporate pan capable of altering local climate and circulation patterns. The framework for deriving rate information and spatial data on volumes for this calculation come from GIS data. Along most of the coast, the sabkha is 10-15 km wide. This area represents an extreme example of seaward progradation in a setting where a sand dune field is being blown into the sea. Radiocarbon age dates at the updip limit of the Holocene range between 4000-6000 years before present, indicating that the entire coastal sand sabkha has built southwestward during this period. The volume of dune sand on the sabkha is one measure of the rate at which sediment is being delivered to the coast. Historical progradation rates are an unlikely source for forward modelling, as water depths and volumes of available sand are likely to have changed over time.

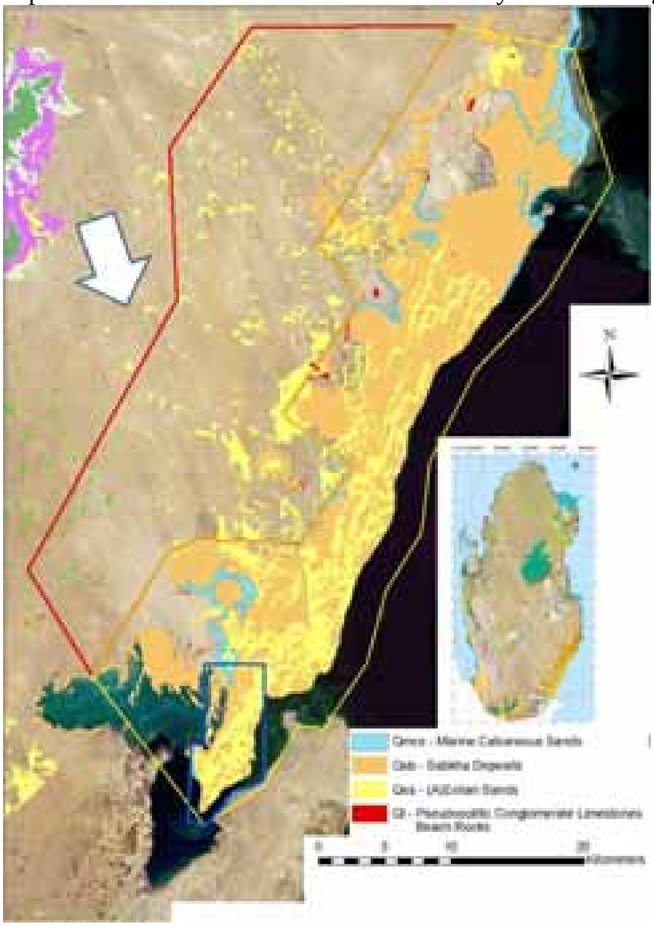


Figure 3A

Figure 3B

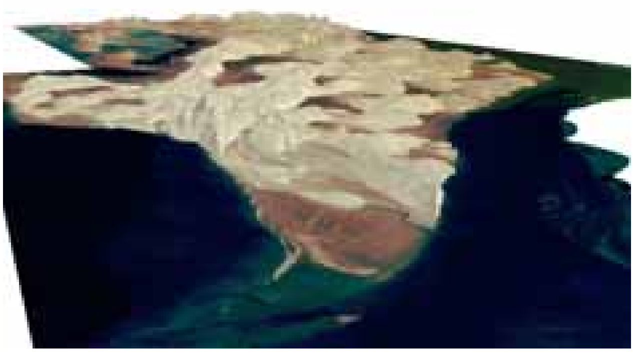


Figure 3C

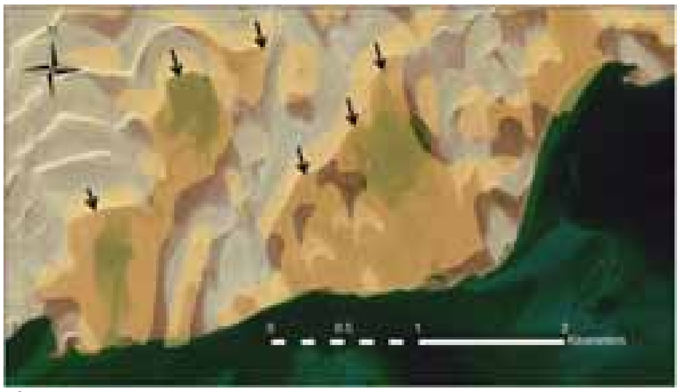


Figure 3D

Figure 3 Example of Use of GIS Data in Forward Modelling and Geological Research

- **A. Overview of south-eastern coast of Qatar at Khor Al Adaid. Volumes of Holocene sand (yellow) and Holocene sabkha (orange) and sea, were measured in order to calculate progradation rates of the coast and predict when the Khor Al Adaid Strait might fill with aeolian sand. Radiocarbon age dates indicate the entire Holocene coast formed in the last 5,000 years. The white arrow shows the prevailing wind direction.**
- **B. Satellite image showing close up view of the area modelled in this paper. Sabkha are coloured orange.**
- **C. Satellite image draped over a vertically-exaggerated DEM illustrates the value of combining various sources of data in an analysis. The exact extent of the DEM and satellite image required for analysis has been extracted through digital geoprocessing of the GIS data. Integration reveals high quality of DEM data, which were used to calculate the total volume of dune sand. Volume and area calculations can be performed to specified reference planes through GIS analytical processing tools. View is from south-west, dune migration direction is from left (west) to right (east). Note the coast protrudes in areas where a dune is at the coast and more recessive elsewhere.**
- **D. Illustration of dune migration rate calculation. Shaded areas are sabkha, as positioned in 1977 and taken from 1980 Seltrust map. Dune images are from 2003 satellite images. Arrows show how dunes have moved in a southerly direction and the distance moved.**

GIS data were used to determine how long it might take to fill in the narrow strait at the southern end of the dune field. Without normal marine circulation, this area known as the Khor Al Adaid Strait (KOS) would likely become an evaporite pan. A similar salt pan development is observed in Dukhan, on the western side of Qatar.

Volumes of sand was derived by GIS determination of volume of the (Qes) polygon above an elevation of 0.5m. Figure 3C illustrates this volume. Dune migration rates were measured by comparison of dune crest and sabkha locations for each polygon, as illustrated in Fig 3D. This analysis revealed that large barchans were migrating an average of 4.4m/year southward. Data were normally distributed with a strong central tendency. The width along dune crest strike formed the third dimension in the volumetric calculation.

Volume sand		
Total area land	36.4	$m^2 \times 10^6$
Volume sand on land	184.5	$m^3 \times 10^6$
Average thickness sand	5	m
Width sand along strike	6450	m
Vol 1 sand into sea 4.4 m/yr	143,636	m^3
Vol 2 sand into sea 3.4 m/yr	110,991	m^3
Vol 3 sand into sea 5.4 m/yr	179,545	m^3
Total volume of sea		
Most Likely	47.6	$m^3 \times 10^6$
Min	42.2	$m^3 \times 10^6$
Max	69.4	$m^3 \times 10^6$
Number years to fill		
Most Likely	332	years
Min	235	years
Max	625	years

Water volume in the KOS was calculated through division of the sea area into sub-polygons of equal depth. Available bathymetry provided reliable values for the shallow areas. In deeper areas a range of possible values was applied.

Results are shown in Table 4. All other factors aside, the strait is likely to fill in 332 years, with a range of 235-625 years. The volume of sand in updip areas is more than adequate to fill in and close the strait. While these figures are approximate, they indicate that other factors, like global sea-level rise, are likely to outpace sediment fill rates. More importantly, this illustrates the role of GIS data in research into coastal processes. Similar analogue studies are used to derive models that are used to condition geocellular reservoir models built by the oil and gas industry.

Table 4.
Data used in calculations for infilling Khor Al Adaid Strait

Geotechnical Applications of GIS in Interpretation of Historical Data for Urban Land Use

The final example illustrates the value of properly registered historical air photo data in urban planning and commercial development. Most of the city of Doha is built on weathered unconformity on the top of the Eocene Dammam formation. The present land surface is a major unconformity that has been subaerially exposed for nearly 30 million years. As a result, cavern systems and karsts are common. Figure 5A and B shows a collapse that was encountered recently, and the hazards they may represent to commercial or residential land use.

Figure 5A and 5B above. Illustrations of surface karst encountered. The feature is much larger than the area of breakthrough.

Example of Geotechnical Applications of GIS from Duhail Area of Doha

Potentially hazardous karst areas were identified through draping the ortho-rectified 1947 aerial photos of the Duhail (meaning "small underground holes or caves") region of Doha over the existing DEM, as shown in Figure 6. Figure 6A shows the original input data and the importance of date metadata ('47' indicating the year 1947) being carried with the image (red ellipse). Figure 6B shows georeferencing the 1947 photograph to identifiable terrain on the satellite image. Subsequent building development has masked some land features. As development occurs in an area, so the opportunities to identify surface features to georeference the 1947 photo are lost. This is where older georeferenced or rectified imagery being retained by the Centre for GIS (UPDA) is so important. This photo was actually georeferenced using a 1995 satellite image.

Figure 6C shows that known karst (on right) has formed along drainages from highs to the south. Karst-prone areas are dark, reflecting surface moisture. The area on the right, with a surface sinkhole, was considered unsuitable for development and made into a city park (Fig. 6F). Surface features similar to those observed in the known surface karst are present along the western side of the image. Dark linear features are present indicating soil moisture. These may explain some of the subsidence problems reported in commercial developments. Some features are not apparent at the surface until revealed through integrated analyses. This illustrates the value of GIS data in urban planning.

Figure 6A Illustration of original data. Image shows the 1947 aerial photo and modern satellite imagery before combination through georeferencing.

Figure 6B Images are combined using transparency in order to allow historical data to identify potential hazards and their impact on commercial and residential development.

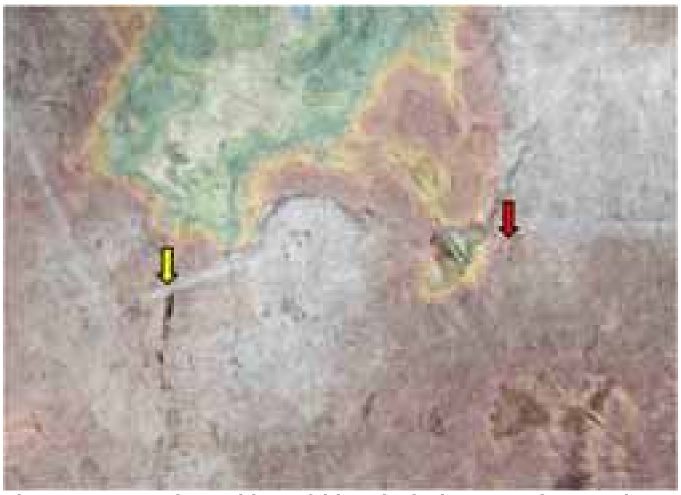


Figure 6C Superimposition of historical photos and DEM shows highlands to south with a dark, prominent drainage on west (left) side and surface karst on east (right) side

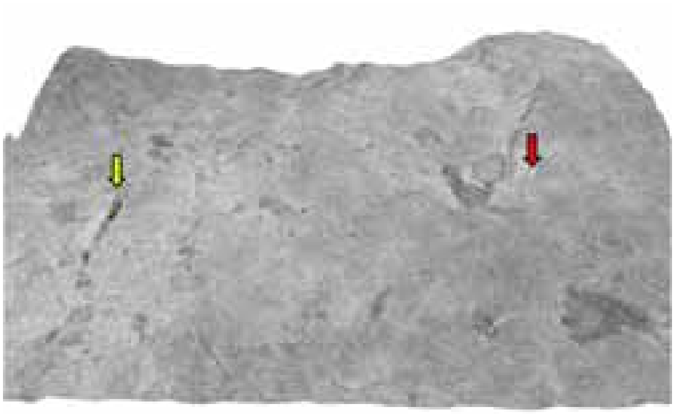


Figure 6D 3-D view from south. Arrows point to known karst (east - red) which was developed as an urban park and a possible karstic drainage (west -yellow) which may account for subsidence problems reported in buildings built above and in road construction.

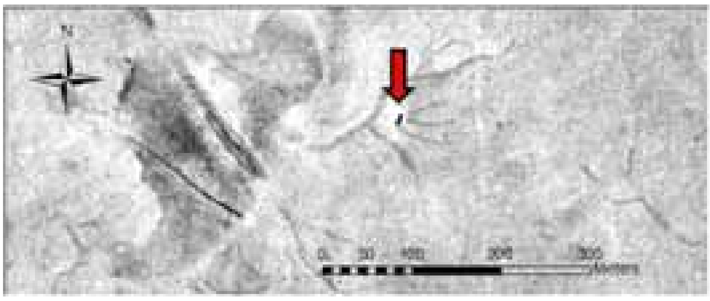


Figure 6E (above left) shows detail of the Duhail park sinkhole in 1947. Figure 6F (above right) shows the sinkhole in the Duhail park.

Figure 6G A 3-D perspective view of Dukhan showing selected geotechnical borehole locations (arrows) in relation to development. A GIS development initiative from Qatar Petroleum's Technical Directorate is integrating all geotechnical borehole and trial pits results data to assist in future planning of construction projects.

Conclusions

GIS is a powerful integration tool in geoscientific analysis. It integrates diverse multi-scale multi-disciplinary spatial data from rock samples to multi-spectral satellite imagery.

Both data and data quality are part of the GIS geodatabase. Metadata in the geodatabase ensures that all available defining information about the data are known.

GIS analytical and geoprocessing tools are valuable for complex analyses. Example functions are volumetrics, geoprocessing, surface analysis, real-time coordinate transformations, image rectification, 2D/3D display and transparency. Techniques and tools used in the studies in this paper include:

- Areas and volumes calculated above reference planes;
- Dune model confirmed by image drape and DEM;
- Polygon clip geoprocessing; define discrete area; update function for surface geology polygons;
- Polygons from lines for easy mapping of surface units;
- Coordinate transformations – WGS 84 in field to local grid;
- Rectifying images and compare with transparency;
- Model and confirm sea-level changes with ArcScene planes;
- ArcScene rotate and exaggeration to view trends and features;
- Metadata – fit for purpose, data gatherer's intent, quality;
- Generate – to generate 3D surfaces from XYZ data;
- Image composition to combine, create and view new RGB image;
- Integrate diverse data sets from sand grain data to satellite data.

GIS enables integrated analyses of data from sand grain size, through feature size to map scale size:

- **Grain size** for: mineralogy; commercial application (e.g. cement production); building material; seismic sound transmission; sand grain source (e.g. sand originates from Saudi Arabia).
- **Surface Feature Size** for: quantifying commercial value (e.g. size of dune and quantity of sand); map feature distribution from aerial images; geological mapping.
- **Map Scale** for geotechnical aspects (i.e. building on cavities or dunes) and strategic planning (should an area be used as an oil field, or a port, a city or a world heritage site)

Summary

While far from comprehensive, the examples given here illustrate the roles that GIS play in the oil and gas industry, commercial development, environmental studies and geological research. With over 60 years of historical GIS data over Qatar being held by the Centre for GIS (UPDA) and Qatar Petroleum, the initiative of twenty years ago is now the mainstay analytical tool. GIS is the boundary where geology meets geophysics and geotechnical engineering. It is a unique database in capturing a wide variety of data, data quality modifiers, an integration tool, and a means of storing analytical methods.

Acknowledgements

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References:

1. Cavelier C., Salatt A. & Heuze Y.(1970)**.** Qatar Geological Map
2. Cavelier C. (1970), Geological Description of the Qatar Peninsula
3. Centre for GIS and Seltrust Engineering Ltd. (1978) GISNet Geological Map of Qatar.
4. Department of Agricultural and Water Research Soils Atlas (2005)
5. Ross R., Applications of a Modern GIS Geodatabase… ,IPTC 2009
6. Ross R., Integrating Remote Sensing and GIS Technologies for Surface Geological Analyses, GEO2010