PS From Plate to Pore: Plate Motion, Paleoclimate, Paleosols, and Porosity in the Permo-Carboniferous Unayzah Reservoir, Saudi Arabia*

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Abstract

Movement of the Arabian Plate from high to low latitudes during Late Carboniferous to Late Permian and the associated climatic changes had profound effects on reservoir quality of Unayzah sandstones. Periglacial braided stream sandstones of lower Unayzah C were deposited in a cold, relatively dry climate. Overlying Unayzah B was deposited as glaciers began to melt depositing glacio-lacustrine sandstones, siltstones, and diamictites. Further northward movement of the Arabian plate, yielded hot-arid conditions during deposition of Unayzah A, and at tropical latitudes warm and humid conditions prevailed during deposition of the fluvio-deltaic to marine Basal Khuff Clastics (BKC).

Clayey paleosols formed during BKC time produced abundant illuviated clay, sesquioxides, and early kaolinite, which in some areas completely plugs pores in underlying sandstones. Less mature paleosols in Unayzah A, associated with brief humid intervals, produced thin clay coats around sandstone grains and preserved primary porosity by inhibiting quartz cementation during deep burial. In addition to pedogenic clay coats, microquartz grain coating associated with silcrete intervals in the Unayzah A also inhibited later quartz cementation. Within the silcretes, brecciated length-slow chalcedony infilled by length-fast chalcedony suggests initial silicification of evaporites under arid conditions followed by remobilization of silica and formation of microquartz during wetter periods.

Coated-grain sandstones in the BKC and upper Unayzah A are often friable and porous. They may have very good or extremely poor permeability depending on thickness of grain coatings. Sand production can be a problem in these friable intervals. In contrast, Unayzah C paleosols are poorly developed or absent. Clay coats are uncommon, and microquartz is absent.

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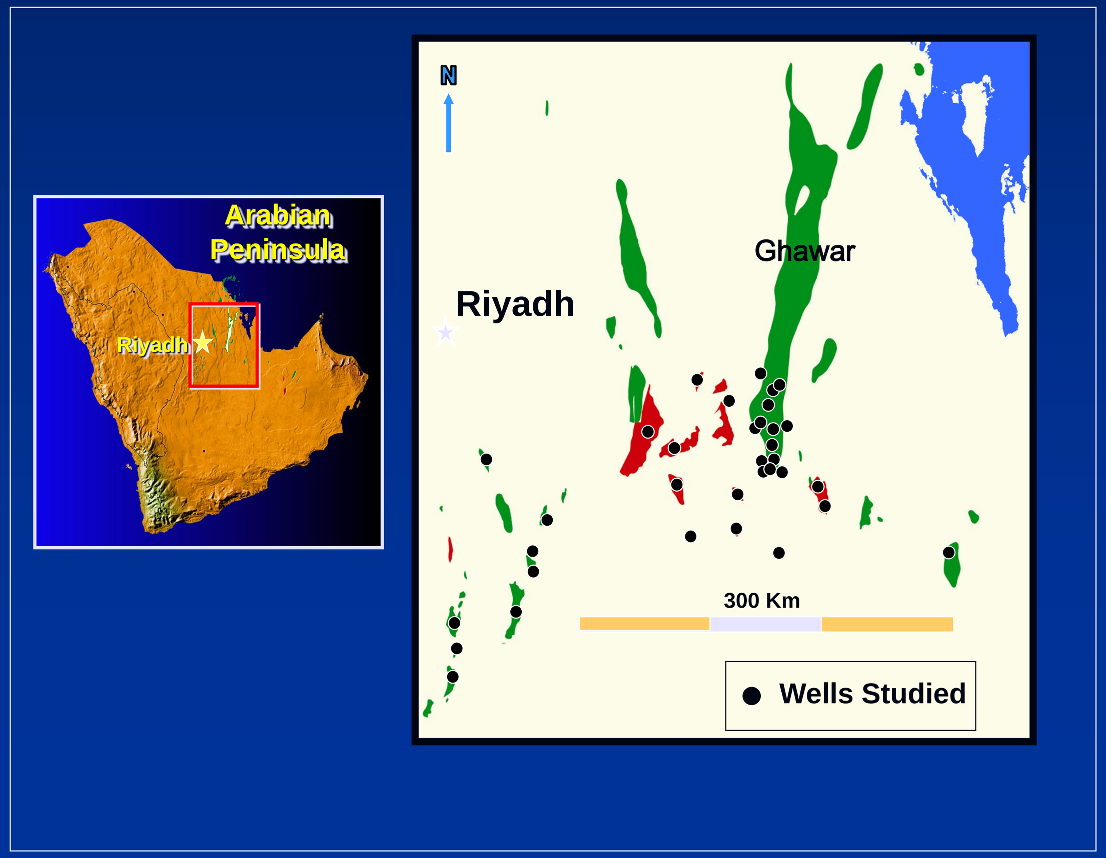
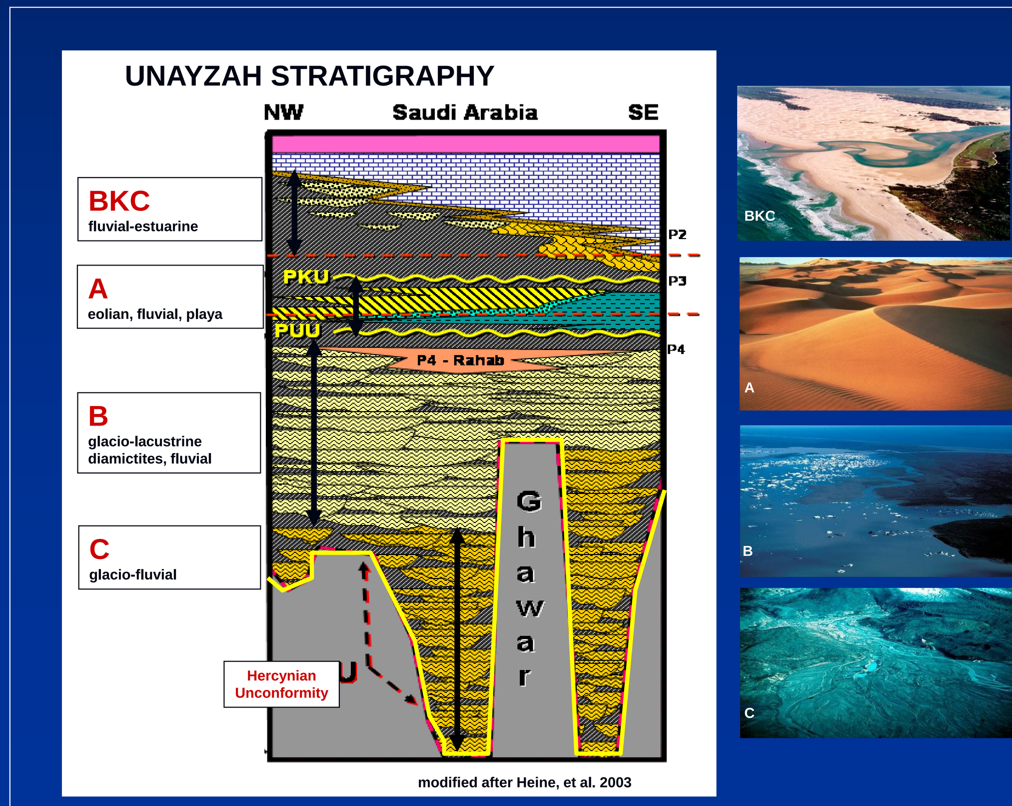
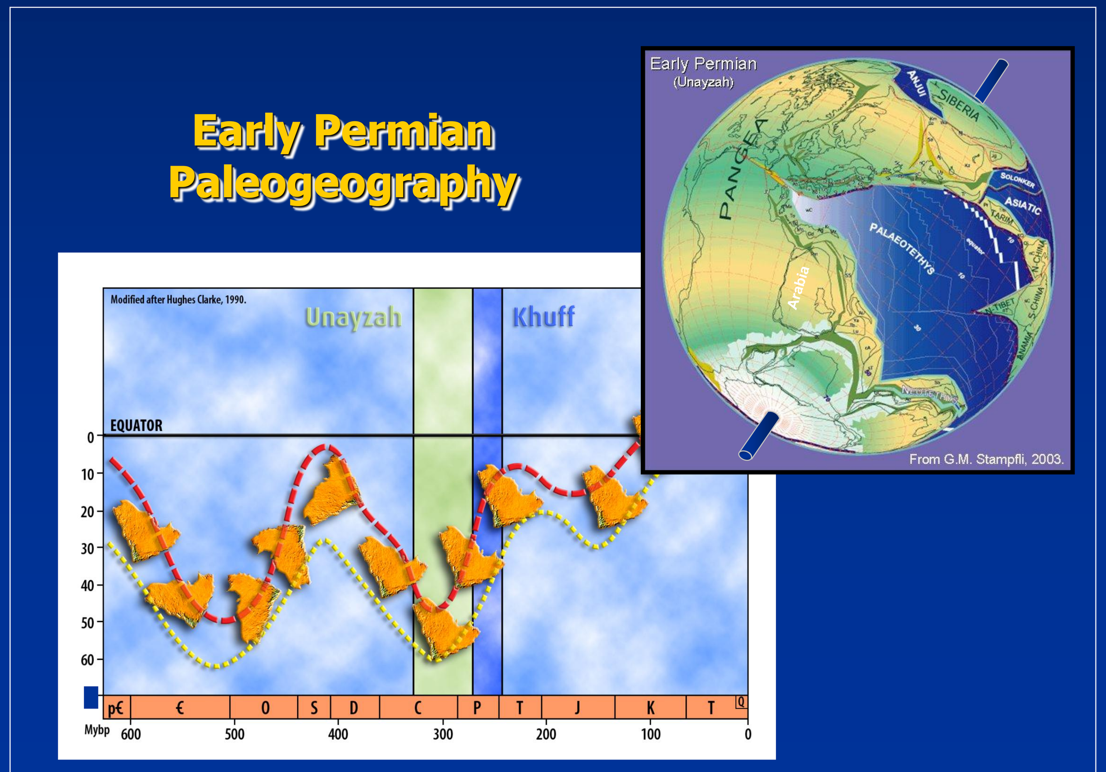
Stephen G. Franks, Saudi Aramco



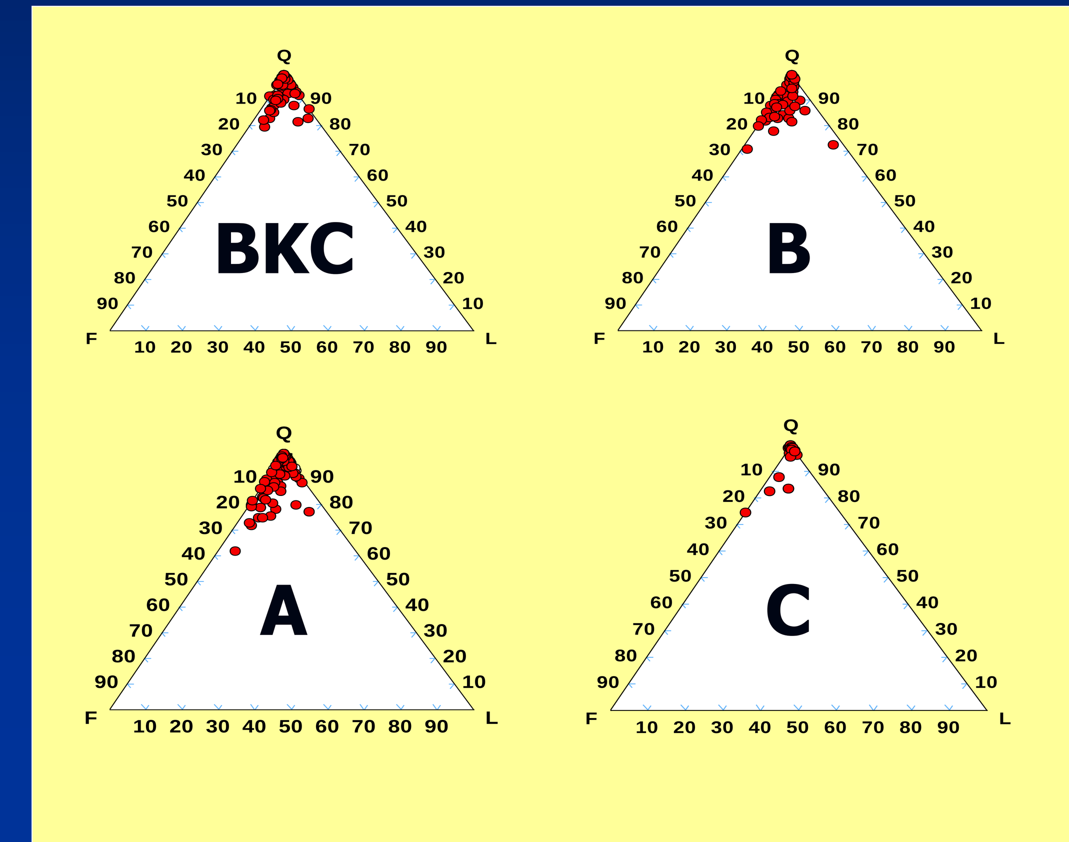
1-Unayzah oil and gas fields of Eastern Saudi Arabia: Oil fields near basin margin (SE corner) are 6000-8000 feet; those at south end of Ghawar are 12000 to >15000 feet deep.



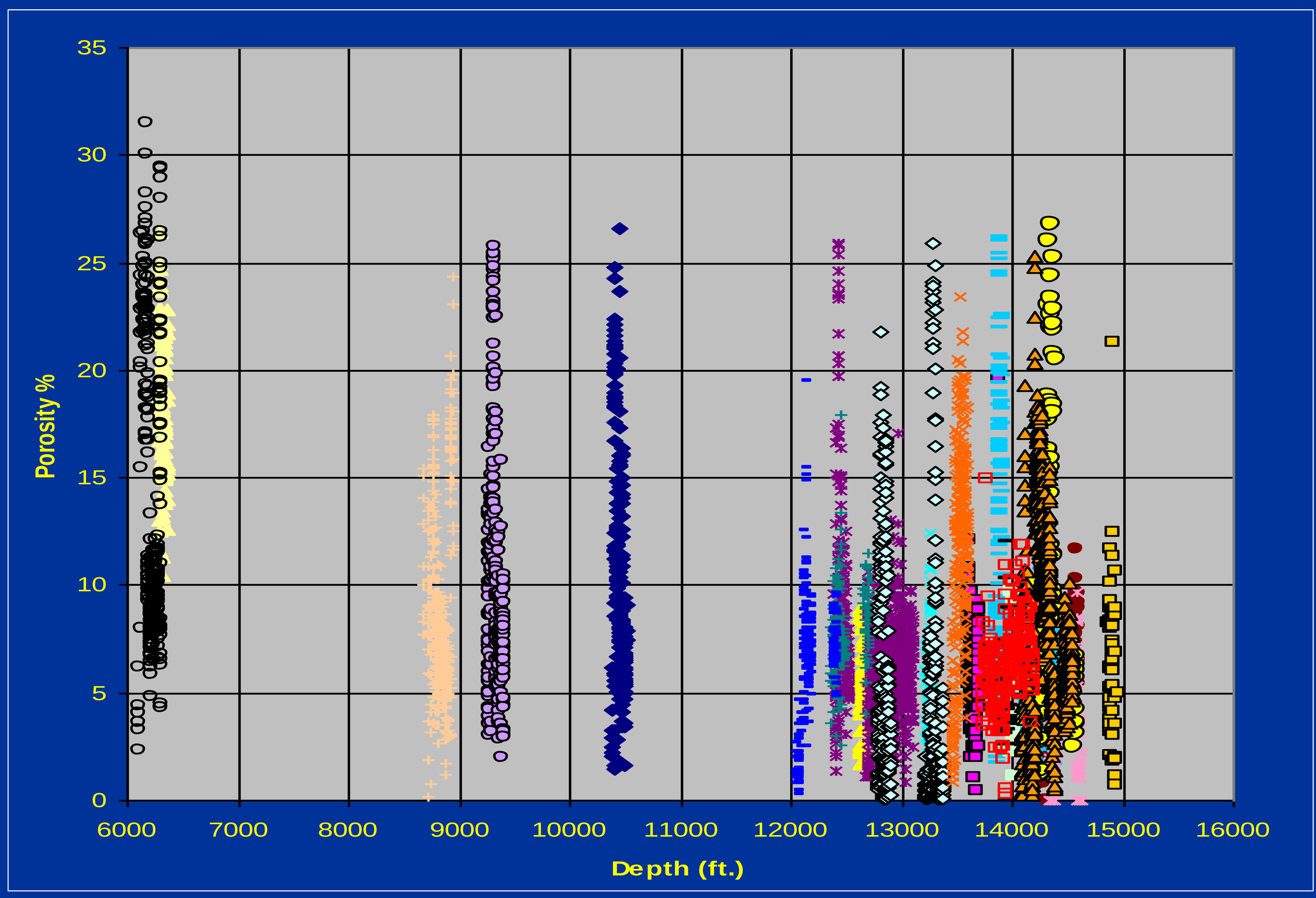
2- Stratigraphy: The “Unayzah Reservoir” is divided into 4 units, from the base these are Unayzah C (resting on the Hercynian Unconformity), B, A, and the Basal Khuff Clastics (BKC). Unayzah C sandstones are glacial outwash, braided stream deposits; Unayzah B are mostly glaciolacustrine & glaciofluvial; Unayzah A are aeolian dunes, interdune, and wadi; BKC are fluvio-deltaic to estuarine.



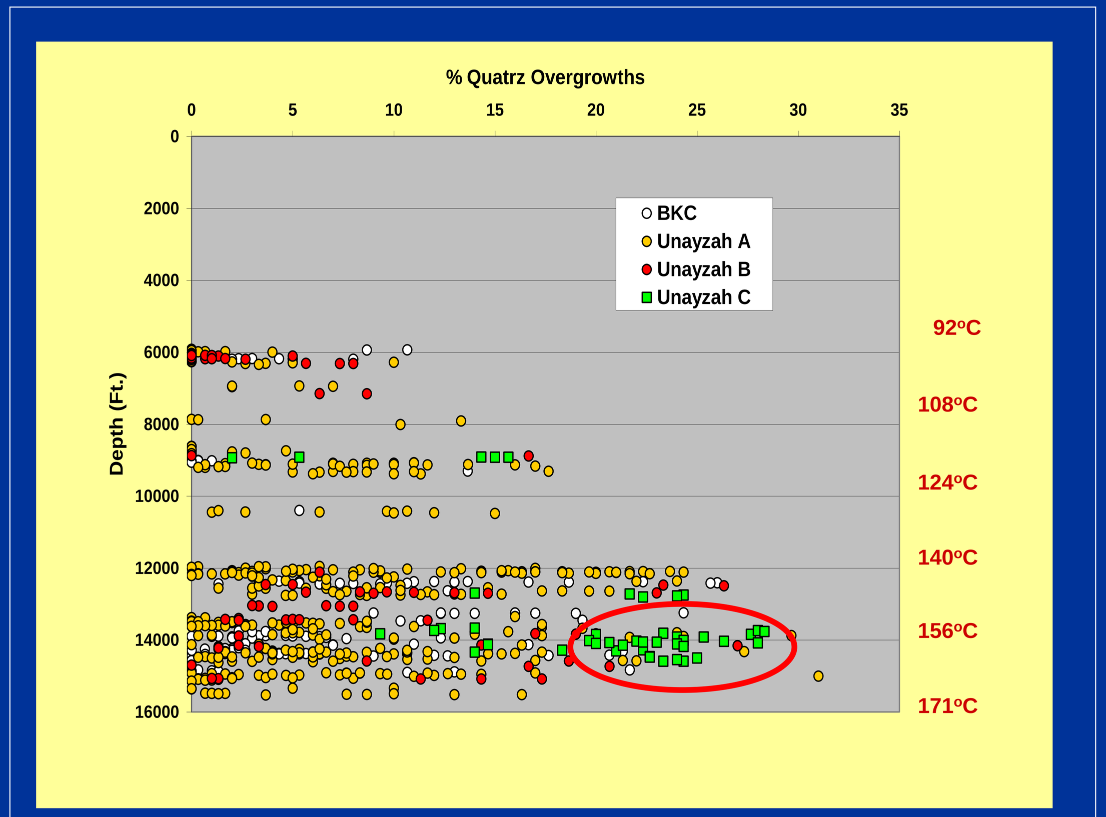
3- The Unayzah was deposited over a period of ~50 million years (green bar) as the Arabian Plate moved from high south latitudes to low latitudes. By Khuff time (blue bar) central Arabia lay at tropical latitudes.



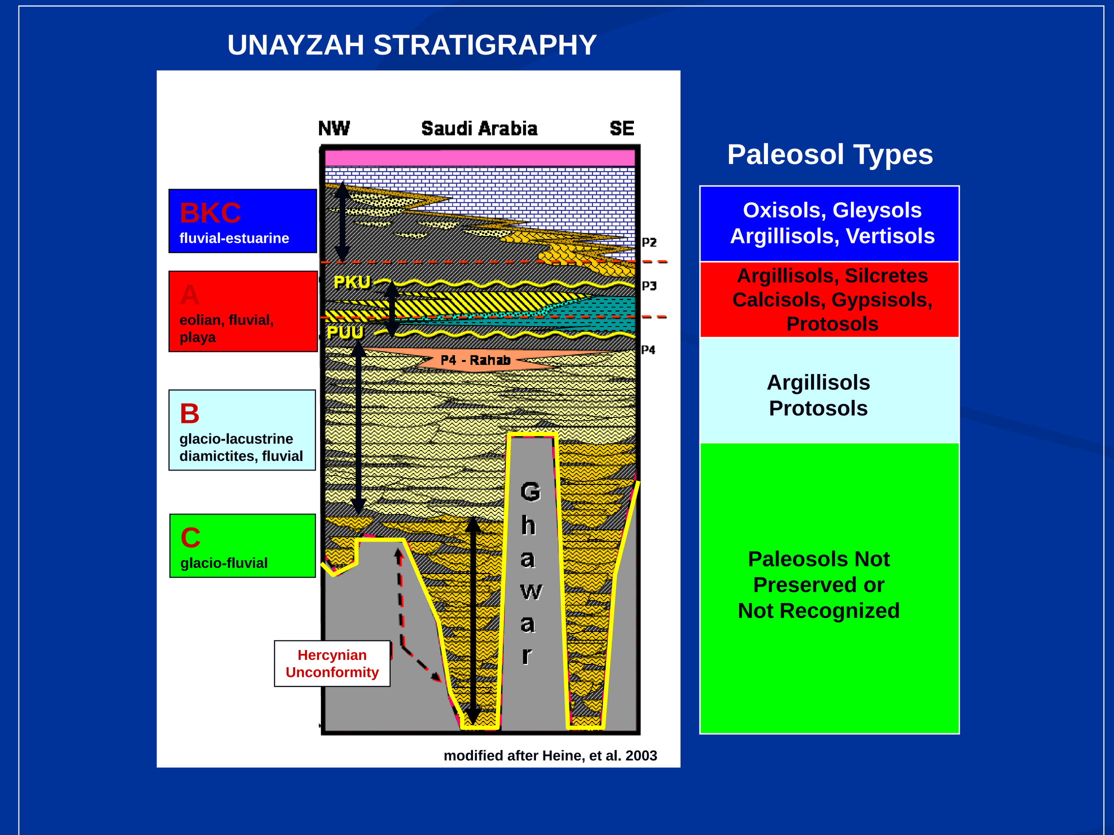
4- Sandstones are mostly quartz arenites to subarkoses; feldspar content increases significantly with decreasing grain size.



5- Average porosity (y-axis) decreases with depth, but porosity varies widely at any depth. Petrographic analysis indicates this is due mostly to variations in texture and quartz cementation. Quartz cementation varies primarily due to differences in degree of early grain coatings, microquartz or clay. These are directly related to pedogenic processes as will be described.



6- Quartz cement generally increases with depth, but varies with stratigraphic unit. It is particularly high in the Unayzah C (circled area) where early grain coatings are virtually absent.



7- The presence of grain coatings is related to pedogenesis associated with paleoclimatic changes, the result of plate movement. The degree of pedogenesis generally increases upward from Unayzah C to BKC. Soils occur more frequently, are thicker, and generally become more argillaceous in the upper A and BKC. They are rare in the Unayzah C. Examples of paleosol cores and thin sections are shown at the top of panel 2. Paleosol classification from Mack, et al. (1993), with the addition of silcretes, is shown to the right.

UNAYZAH PALEOSOL CLASSES

(USING CLASSIFICATION OF MACK ET AL. ,1993)

OXISOL- The prominent process is extensive alteration of chemically unstable minerals to clay and sesquioxides. The most common type of 1:1 clay is kaolinite, whereas hematite, goethite, and gibbsite are the most likely sesquioxides.

GLEYSOL- The prominent feature is a horizon with evidence of low redox conditions, e.g. colors of low chroma (greys and greens), carbonaceous material, pyrite.

VERTISOL- Prominent feature is evidence of homogenization of the profile by pedoturbation due to shrinking and swelling of expandable clays: dessication cracks, wedge-shaped peds, hummock and swale structure, slickensides, and clastic dikes.

ARGILLISOL- Most prominent feature is a horizon containing illuvial clay (argillic horizon); clay coats on peds, oriented clay linings in vughs or on planes, clay coats on detrital grains. (Common in the modern order, Alfisols and Ultisols).

CALCISOL- A calcic horizon (enriched in calcium carbonate or dolomite) is the prominent feature. Scattered carbonate nodules and tubules, brecciation, and pisoliths may be present. (Common in the modern order, Aridosols).

GYPSISOL- Pedogenic gypsum or anhydrite precipitated in the vadose zone is the key criterion.

PROTOSOL- Characterized by weak development of horizons (but not due to pedoturbation). May include features such as argillans (clay coats) are carbonate, but these are too poorly developed to be considered the most prominent features. (Common in modern order, Inceptisol and Entisol).

SILCRETE- Defined here as paleosol where the dominant characteristic is the presence of pedogenic silica (e.g. cryptocrystalline silica, chert, chalcedony). [This is not included by Mack, et al. (1993) as one of their types. They would call these Siliceous Argillisols.]

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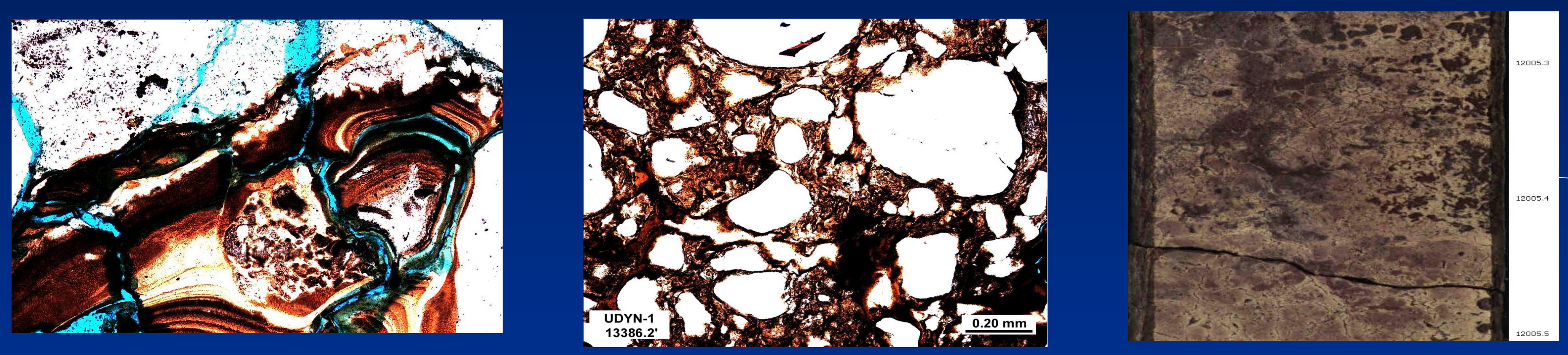
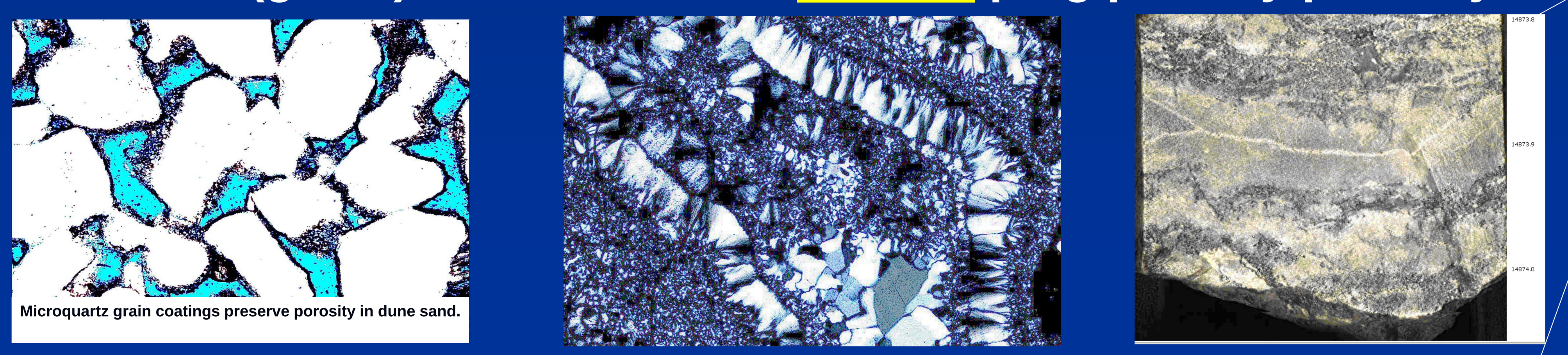
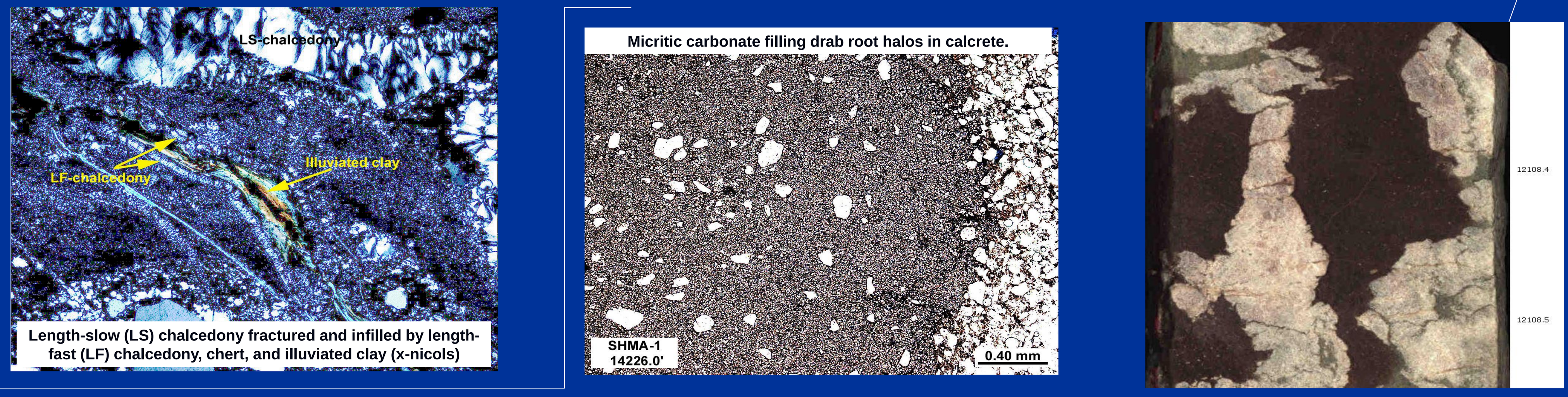
THINSECTION PHOTOMICROGRAPHS — CORE PHOTOS



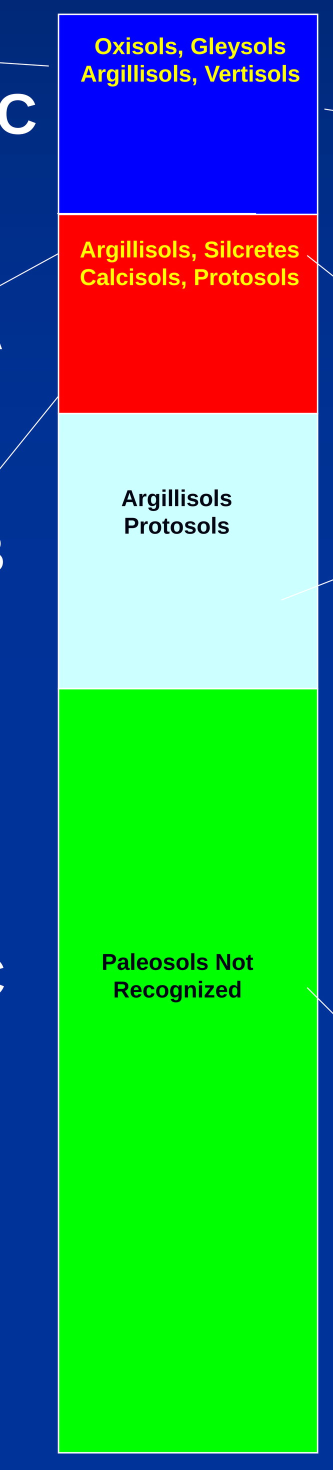
FeOx (gels?) and kaolinite in **Oxisols** plug primary porosity.



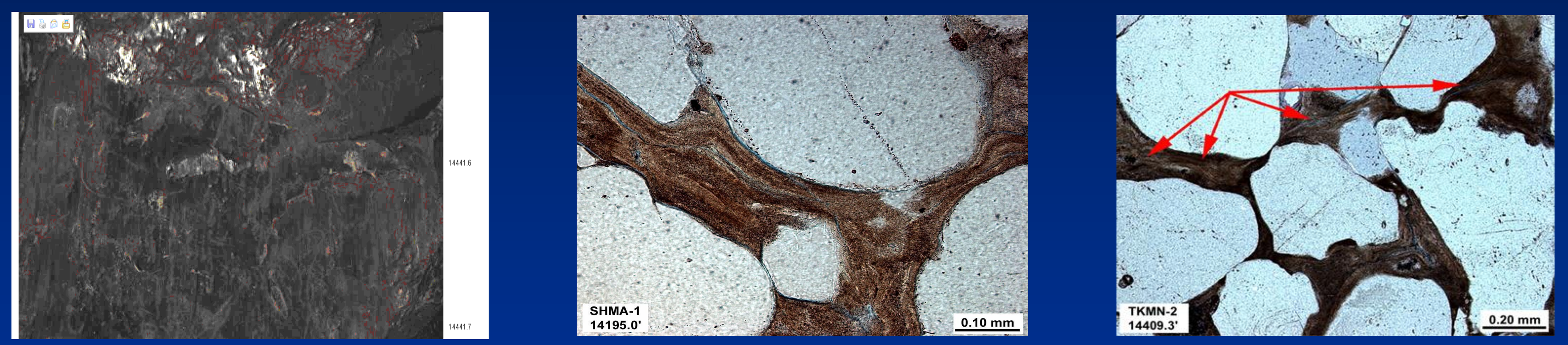
Microquartz inhibits cementation in sands associated with **Silcretes**.



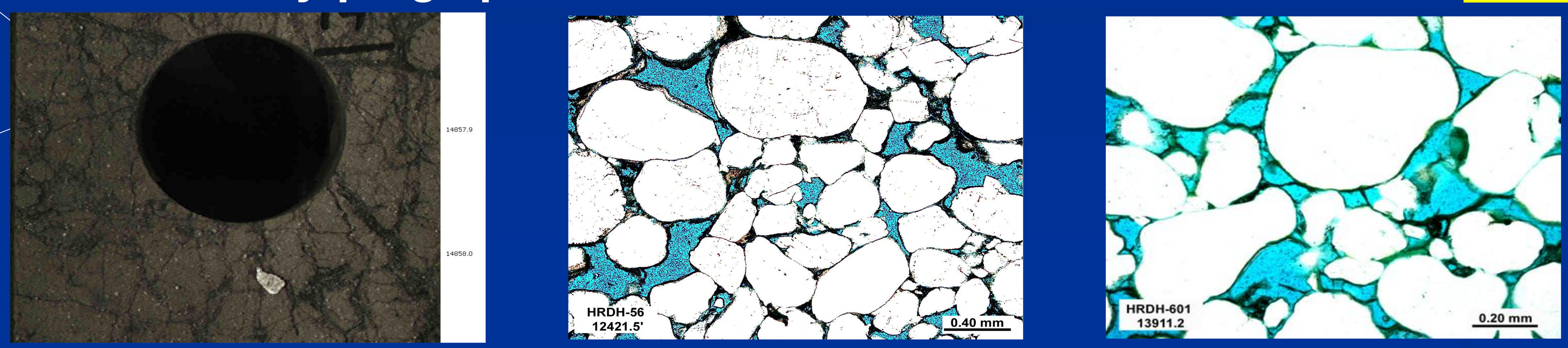
Calcisols mostly occur in non-reservoir red siltstones of Unayzah A.



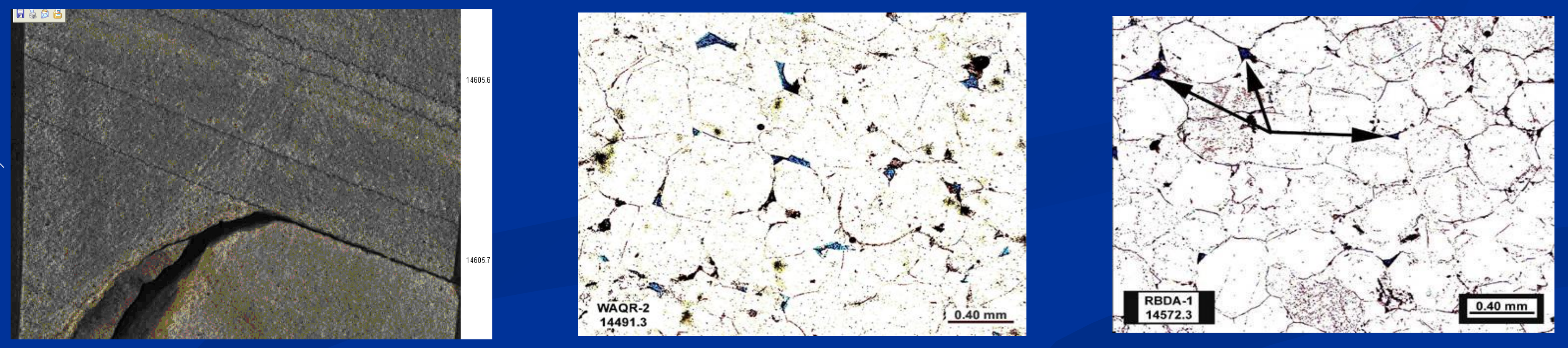
CORE PHOTOS — THINSECTION PHOTOMICROGRAPHS



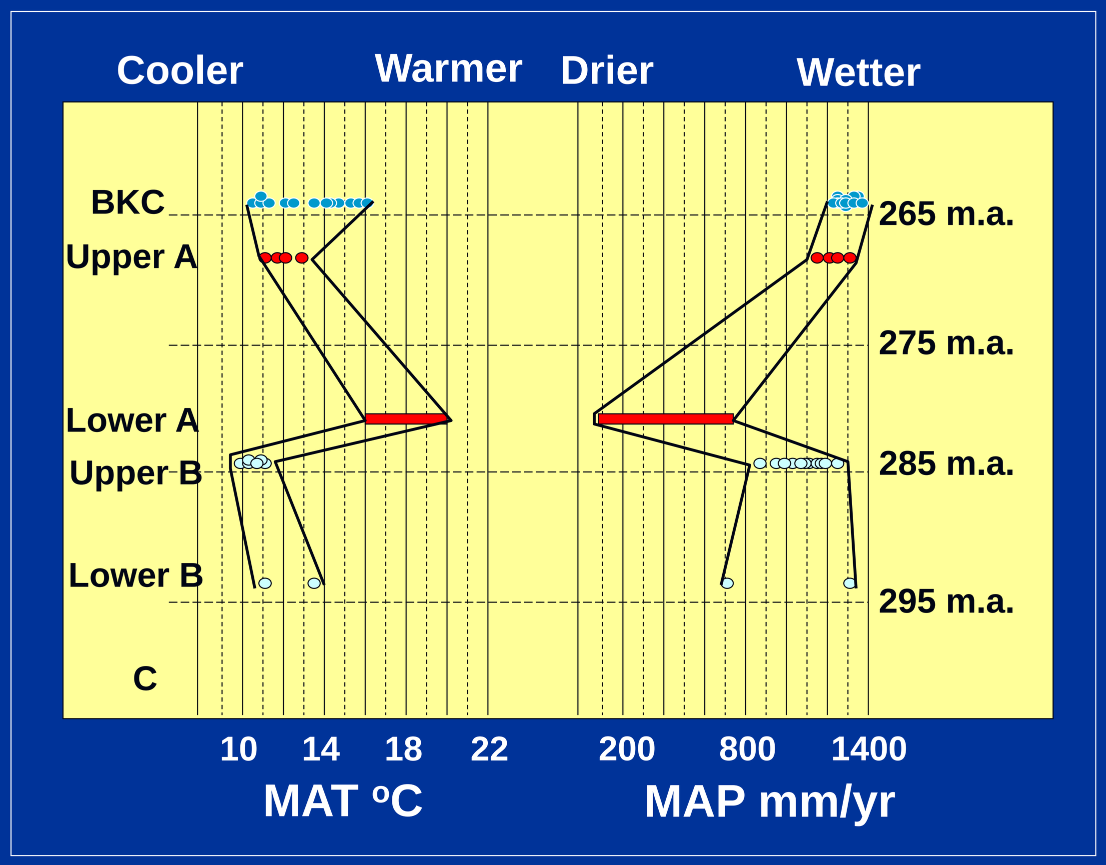
Illuviated clay plugs pores in sandstones associated with thick **Vertisols**.



Argillisols and **Protosols** yield thinner clay coats & inhibit quartz cement.



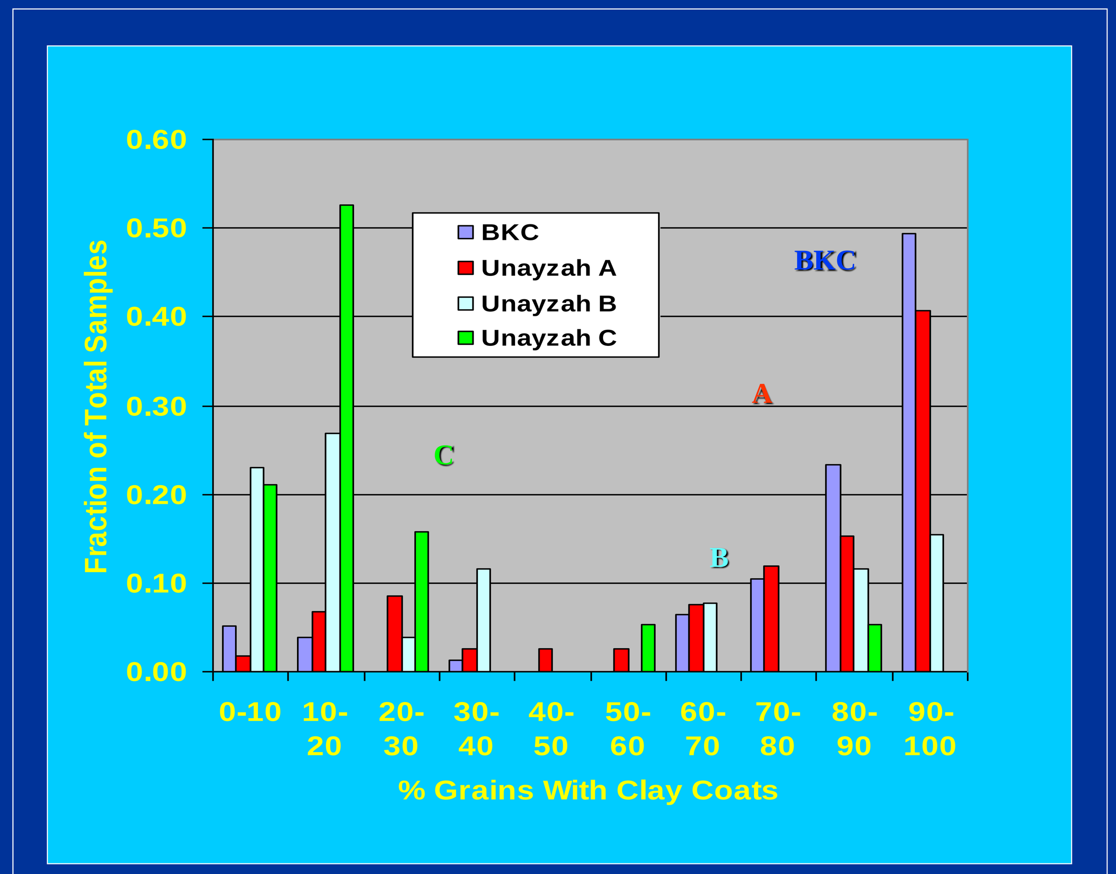
No paleosols in Unayzah C, no clay coats, intense quartz cement.



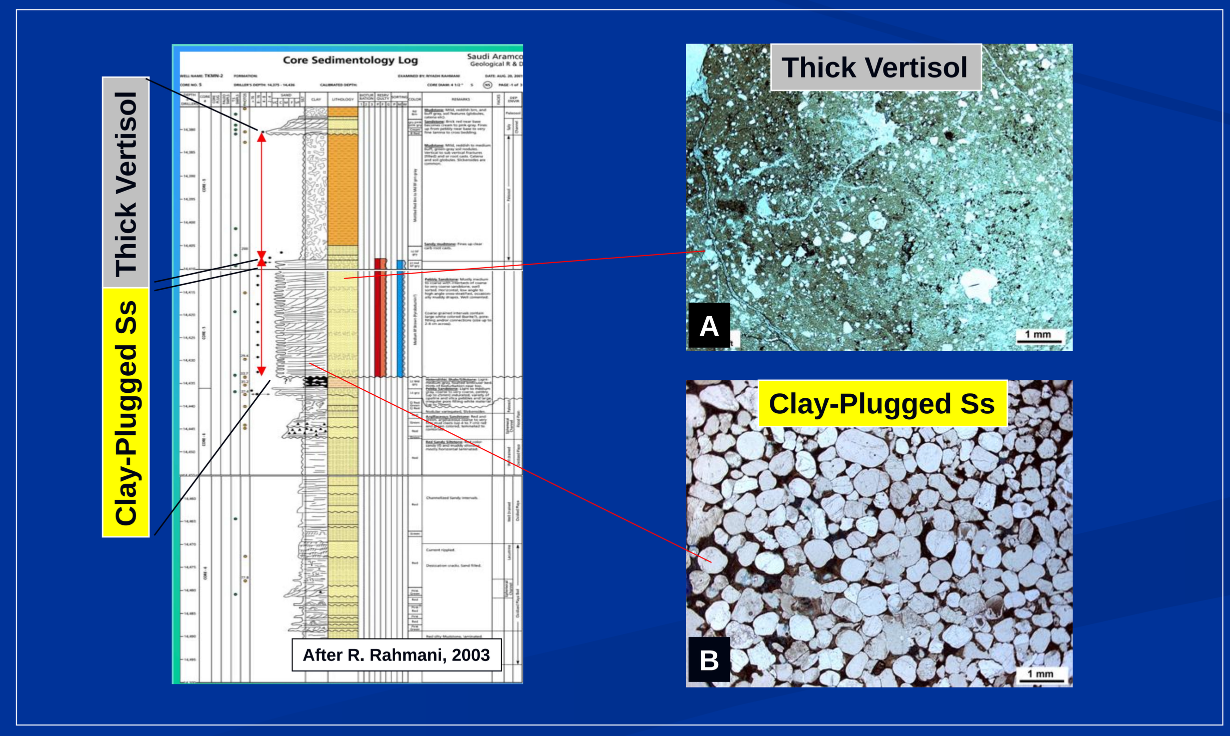
8- Oxide ratios of Unayzah paleosols suggest cooler mean annual temperatures (MAT) in B and warmer temperatures in the A and BKC. Mean annual precipitation (MAP) increases in late Unayzah A and BKC time. Oxide ratios (Sheldon et al., 2002) are not valid for Calcisols (red bars). Their MAT and MAP are based on constraints of Goudie (1983). MAT estimates from oxides are generally much less robust than MAP (see below.)

$$MAT(^oC) = -18.516(Na_2O + K_2O/Al_2O_3) + 17.298 \quad (R^2 = 0.50)$$

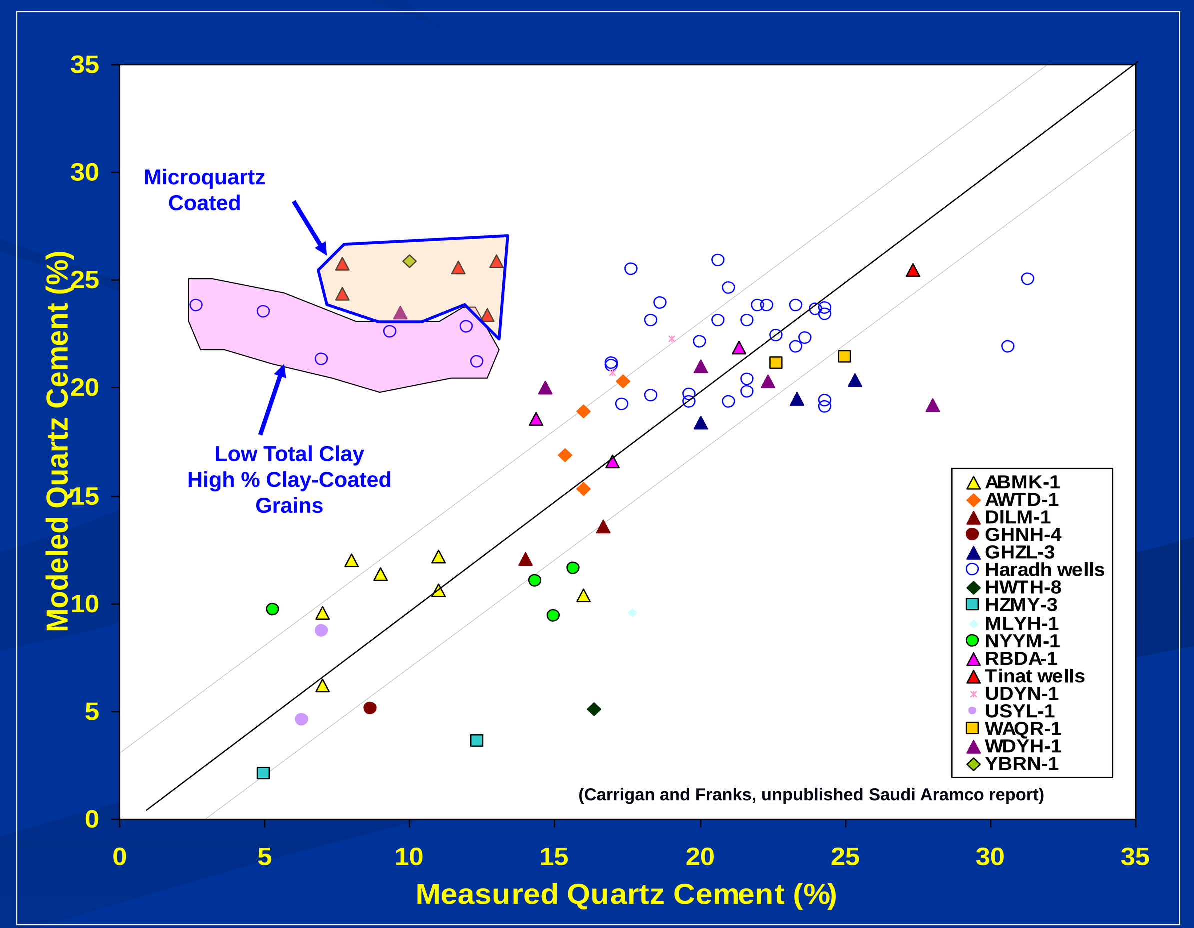
$$MAP\ (mm/yr) = 14.265(Al_2O_3{+}Na_2O{+}CaO/Al_2O_3) - 37.632 \ (R^2 = 0.73)$$



9- The percentage of coated grains increases systematically from Unayzah C to BKC. 85% of samples in C contain less than 20% coated grains. About 80% of BKC sandstones have 70% of their grains coated with clay or microquartz. These differences are related to paleoclimate and pedogenesis directly related to paleoclimate or plate position (paleolatitude) . See core photos & photomicrographs above for examples of effects of paleosols.



10- Pedogenesis can also destroy reservoir quality. Example above shows a thick sequence of vertic paleosols (>25 ft. vertisol- thin section A, above) overlying ~25 ft. of well-sorted, originally clean, porous sandstone. The porosity of the sandstone has been eliminated by illuviated clay from the overlying soils (thin section B, above). Only the lower 2 feet of the sand retains some porosity.



11- Quartz cementation is predictable *if* the degree of grain coating can be anticipated. If coats are not taken into account, models over-predict the amount of quartz (see clay and microquartz coated samples highlighted above). Corrected for coats, these points move to the right, within the dotted lines (±3%). Due to the complexity of factors controlling pedogenesis, predicting grain coatings prior to drilling remains a challenge and is an area of active research.

CONCLUSIONS

1- Present-day porosity and permeability in the Unayzah Reservoir is a function of the presence and amount of coated grains (either clay or microquartz) which inhibit burial diagenetic quartz overgrowths.

2- The types and amount of coated grains are related to pedogenic processes which are a function of paleoclimate and ultimately plate tectonic movement of the Arabian Plate.

3- Thick vertisols and oxisols mostly in the BKC tend to plug porosity of associated BKC sandstones and underlying upper A sandstones with sesquioxides, illuviated clays, and early diagenetic kaolinite.

4- Less well-developed, thinner argillisols and protosols of the Unayzah A and B tend to produce thinner clay coats which help preserve porosity by inhibiting burial diagenetic quartz cementation.

5- Sandstones associated with silcretes and siliceous argillisols may have their porosity preserved by early microquartz grain coatings.

6- Paleosols are not recognized or are non-existent in the cold-climate Unayzah C, and clay coats are rare. As a result the sandstones are tightly cemented with burial diagenetic quartz overgrowths.

8- Kinetic models of quartz cementation fairly accurately predict quartz cementation and porosity in the Unayzah when grain coatings are taken into account in modeling.

9- The variation in degree and type of pedogenesis complicates pre-drill porosity prediction in the Unayzah.

10- The key challenge is predicting the occurrence of early grain coatings prior to drilling. This is an area of active research for Saudi Aramco.

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Mack, G.H., W.C. James, and H.C. Monger, 1993, Classification of paleosols, Geol. Soc. Amer. Bull., v. 105, 129-136.

Sheldon, N.D., G.J. Retallack, and S. Tanaka, 2002, Geochemical climofunctions from North American soils and application to paleosols across the Eocene-Oligocene boundary in Oregon, Journal of Geology, v. 110, 687-696.