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# Subsurface hydrology in Lake Chad basin from space-based and hydrogeological data

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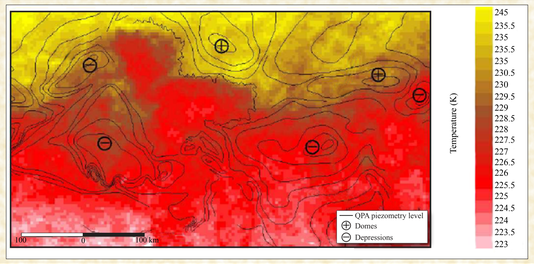
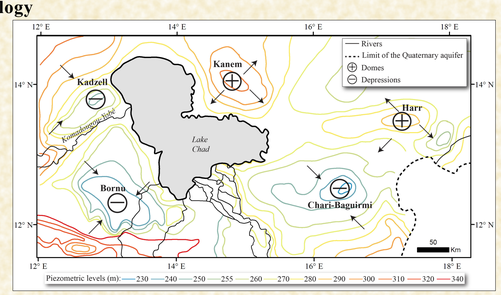
**Abstract:** In the Lake Chad basin, the Quaternary Phreatic Aquifer (named hereafter QPA) presents large piezometric anomalies referred as domes and depressions.[1] discovered that brightness temperatures from METEOSAT infrared images of the Lake Chad basin show a correlation with the QPA piezometry. From this observation, these authors suggested that this thermal behaviour results from an evapotranspiration excess above the piezometric depressions. This model implicitly assumes that the QPA is hydrodynamically separated from the other aquifers by the clay-rich Pliocene formation. However during present study, some giant polygons have been discovered that demonstrates the vertical connectivity of the different aquifers. Temperature profiles in oil wells suggest that convection occurs within the basin. Accordingly, a numerical convective model is developed.

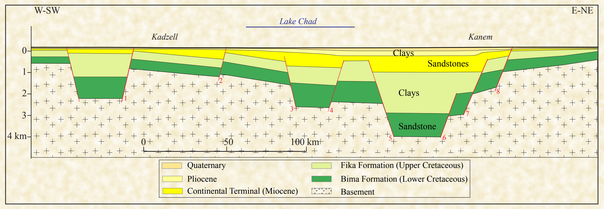



## *Formation of the piezometric anomalies*

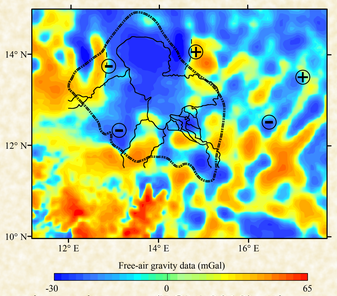
### Hydrogeology



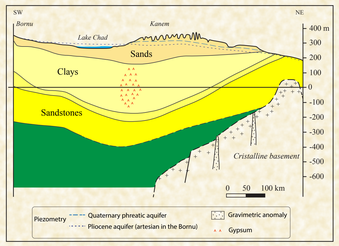

The Quaternary Phreatic Aquifer (or QPA) forms an extensive reserve covering ~500,000 km². It presents large piezometric anomalies as the Kanem and Harr piezometric domes and the Kadzell, Bornu and Chari-Baguirmi piezometric depressions [2]. The depths of these piezometric anomalies are ~15 m and ~60 m, respectively.




The geological SW-NE synthetic cross-section (modified from [4]), through the Kadzell to the Kanem regions indicates that the detritic sediment cover is fan-shaped and oriented toward east. Indeed, the thickness of the sediment succession ranges from ~850 m under the Kadzell region to ~4,000 m under the Kanem region



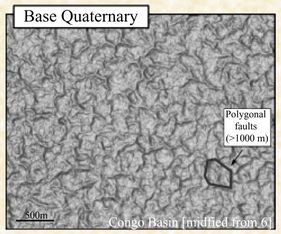

Regional free-air gravity map (EGM 2012). The superimposition of the piezometric contours with this gravity map reveals that piezometric domes and depressions are located on or close to normal faults (dashed lines), delimiting the basin [3].



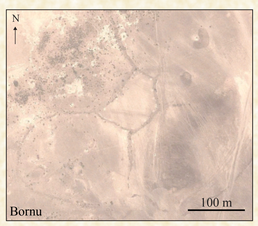

Geological cross-section of the upper part of the sediment infill from Bornu to Kanem [modified from 2]. It shows an increase of the Pliocene and Quaternary formations thickness, located below Kanem.

### Vertical permeability through clay formations

The upward migration of the fluid in the clay-rich formations is extremely slow because of their small permeability (<< $10^{-15}$ m²). At the centre of the graben, delimited by the faults 5 and 6, the Fika formation has a ~2,000 m thickness and stands at a mean depth of ~1.5 km. It is thus likely that it has lost about 40% of its interstitial water [5], inducing a ~800 m of vertical shortening. Accordingly, this compaction movement may induce fracturing of the clay at the vicinity of faults 5 and 6, permitting the hydrodynamical connexion between the Bima and Fika formations.

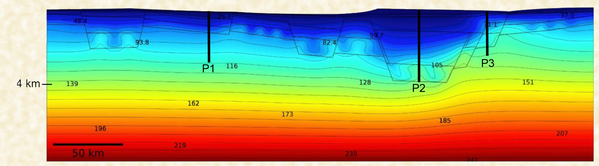



The Fika blocks delimited by the faults 1-2-3-7 and 8 are not expected to be notably compacted, because of their shallow depth. However, in sloped undercompacted clay horizons of ocean margins, giant polygons are generated by extensional horizontal stresses [6].

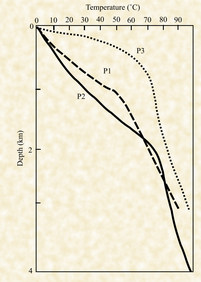



Slope breaks are observed in the surface topography over Bornu, Kadzell and Kanem and thus, the Pliocene formation must be affected by few MPa horizontal tensile stresses. We discovered the existence of giant polygonal fractures in the Bornu region.

### Large-scale groundwater convective circulation

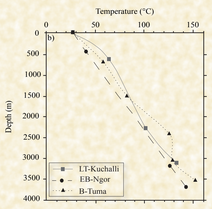



Convective temperature field within the Lake Chad basin, after 500,000 yrs. Due to the large scale eastern tilt of the isotherms of the conductive field, a convective cell crossing the whole basin is generated. It descends along the western border of the basin below the Kadezll (heat flow: 30-60 mW $m^{-2}$), then flows toward east in the Bima formation and finally rises along faults 6 and 8, below the Kanem (heat flow: 120-170 mW $m^{-2}$).

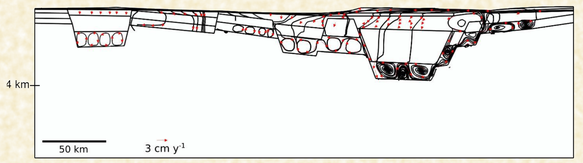



Temperature profiles are extracted from our model, crossing Kadzell (P1), the centre of the graben (P2) and Kanem (P3).When the profile is concave the current is descending, and when it is convex, the current is ascending.

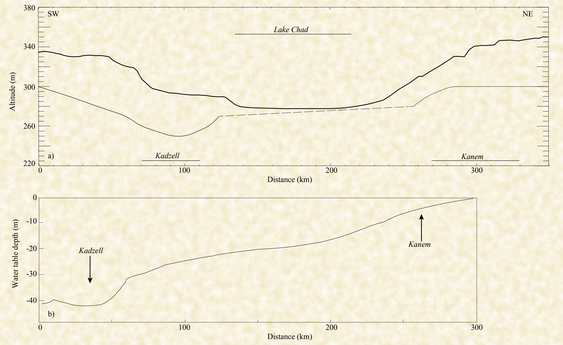
- P1shows a slightly cooling before the purely conductive transport in the basement.
- P2 shows a cooling before a warming of the graben induced by a small warm ascending plume
- P3 shows a warming of the temperature sediment due to the warm ascending plume that develops below the Kanem.




Thermal profiles obtained by [7] can be compared to those of our model. In the ancient bed of Lake Chad, there is a warm ascending current (LT-Kuchalli). In the Bornu area, profile B-Tuma has a notable concavity indicative of a descending current. The last kilometre of the profile is indicative of the presence of a bottom convective boundary layer. Outside the Bornu depression, profile NB-Ngor does not present any concavity. It suggests that the transport of heat here is purely conductive.



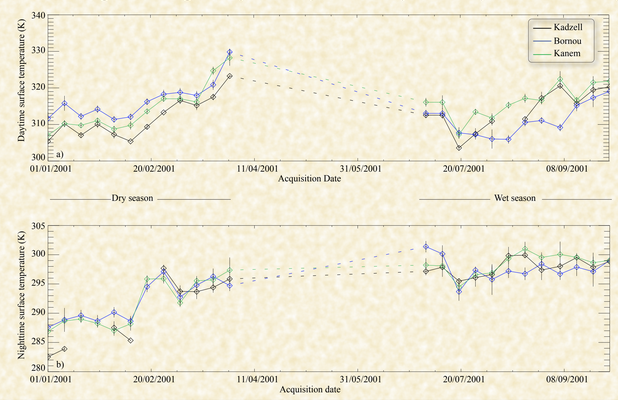

Streamlines (flow lines), as well as the fluid velocity (queues of the red arrouw are proportionnal to the logarithm of the velocity amplitude). The water enters in a diffure way below the Kadzell region. Its Darcy velocity is 4 mm $yr^{-1}$. This fluis is then transported through the large-sacle convective cell within the Bima formation at a mean velocity of 2 cm $yr^{-1}$. Meanwhile, it is warmed by the basement and flows up to the surface below Kanem with a velocity of 10 cm $yr^{-1}$ in the ascending warm plume. When the water reaches the surface, a back-flow is generated toward west.




When comparing the observed piezometric water table (a) with the modelised pressure difference (0.35 MPa) between the descending current below Kadzell and the ascending plume below Kanem (b), both profile correctly matches.

## *Correlation between the spatial thermal data and the convective circulation*

Daytime and nighttime 8-day composite MODIS Terra maximal surface temperatures obtained during 2001. These temperatures are acquired for the Kanem, Kadzell and Bornu regions during the dry season (from January to March) and the wet one ( from July to September).




At both seasons, Kanem is ~4 K (during day)/ ~2 K (during night), warmer than Kadzell. In order to explain this temperature difference, we must consider the water condensation at the Kanem surface. During night, the condensation of 1 mm per day of this water heats the Kanem surface by 1K. During the dry season, the existence of perennial pounds in the Kanem region is linked to the piezometric dome, supplied by the warm ascending current and explains why this region remains warm as the evaporation/condensation cycle still occurs.

During the wet season, Kanem is ~5 K warmer than Bornu during day while at night, the temperature drops to ~2 K. However, during the dry season, the situation is reversed. This last observation may be linked to the presence of vegetation in the Bornu and the proximity of Small Lake Chad and the Chari-Logone rivers. Indeed, a most part of the humidity condensated at night is absorbed by the vegetation and it is no more available to evaporate during day.

**Conclusion:** Our numerical convective model shows that beneath the depressions, a cold descending convective current sucks the QPA and forms the piezometric depressions. Meanwhile a warm ascending current creates an overpressure in the QPA and forms the piezometric domes. The heat provided by the warm ascending current below Kanem is not sufficient to explain the 1 to 2°C brightness temperature difference observed with Kadzell at night. In order to explain this temperature difference, we must consider the heat provided by the condensation of humidity during night. In this case, the role of the ascending current is to provide water at the surface to maintain a minimal rate of humidity whatever the season. To conclude, the use of thermal images in order to detect ascending water currents near the surface results from the combination of i) the presence of a highly permeable surface and ii) the presence of warm zones during day and night and whatever the season. Future improvements of our model should lead to incorporating surface exchanges as evapotranspiration diurnal cycle.

**References:** [1] Leblanc, M, et al. (2003) Application of Meteosat thermal data to map soil infiltrability in the central part of the Lake Chad basin, Africa. Geophys. Res. Lett. doi:10.1029/2003GL018094; [2] Schneider, J L, Wolff, J P (1992) Carte Géologique et Hydrogéologique à 1/1 500 000 de la république du Tchad. Mémoire explicatif, B.R.G.M.; [3] Avbovbo, A A, et al. (1986) Depositional and structural styles in Chad basin of Northeastern Nigeria. The American Association of Petroleum Geologists Bulletin, 70 (12):1787-1798; [4] Pouclet A, Durand, A (1983) Structures cassantes Cénozoïques d'après les phénomènes volcaniques et néotectoniques au nord-ouest du lac Tchad (Niger Oriental). Ann. Soc. géol. Nord CIII ( France)143–154; [5] Sclater, J G, Christie, P A F (1980) Continental stretching: An explanation of the Post-Mid-Cretaceous subsidence of the central North Sea Basin. J. Geophys. Res. doi: 10.1029/JB085iB07p03711; [6] Gay, A, et al. (2004) Polygonal faults-furrows system related to early stages of compaction – upper Miocene to recent sediments of the Lower Congo Basin. Basin Res. doi: 10.1111/j.1365-2117.2003.00224.x; [7] Nwankwo, C N, Ekine, A S Geothermal gradients in the Chad basin, Nigeria, from bottom hole temperature logs. Scientia Africana, 9 (1):37-45.