AAPG HEDBERG CONFERENCE
"***Variations in Fluvial-Deltaic and Coastal Reservoirs Deposited in Tropical Environments***"
APRIL 29-MAY 2, 2009 – JAKARTA, INDONESIA

Tropical Fluvio-Lacustrine Complexes of Africa and SE Asia: Implications for Exploration and Development

Rob Crossley
Fugro Robertson Ltd, Llandudno, Wales, LL30 1SA, UK

This paper discusses some of the deposits of the soil-fluvial-swamp-delta-lacustrine complexes that together make up the reservoir-source-seal trilogies encountered in many of our petroliferous humid tropical non-marine basins. It becomes evident that sedimentary process models developed in mid to high latitudes are not fully appropriate to the humid tropics, and that exploration and development in basins containing these facies would benefit from additional research and new geotechnical approaches.

HUMID TROPICAL SOILS: If properly understood, these soils can help correlate between wells for development projects, can help constrain the depositional setting of associated reservoir, source and seal facies, and can provide palaeoclimatic proxies.

Soil physics and chemistry: Poorly drained tropical soils develop clays which exhibit strong shrinkage/swelling during annual dry season/wet season couplets, and over time the net result is "churning" of the soil and pervasive development of curved, slickensided, clay-coated, slip surfaces. Such pedogenic surfaces can usually be reliably differentiated from tectonic and coring-induced slip surfaces in core.

Pedogenic gypsum can form in the humid tropics, during the dry season in poorly drained settings receiving groundwater from sulphur-bearing rocks (eg. pyritic shales). Some of the gypsum remains in the soil through the wet season, in places giving accumulations that are sufficient for local scale mining. Minor amounts of gypsum (or, after burial dehydration, anhydrite) in our Tertiary sequences may therefore indicate that precipitation (P) is less than evaporation (E) seasonally, rather annually.

Pedogenic carbonate in the humid tropics is generally a characteristic of poorly drained soils and seasonal aridity. However, in better drained settings carbonate concretions can be strongly developed beneath termite mounds. This is due to the "umbrella" effect of the mounds preventing percolation by meteoric water, combined with carbon enrichment courtesy of the plant debris carried into the mounds by the termites, and the inorganic carbon in unleached particles carried up from the subsoil to build the mounds.

Tropical soil biota: Where precipitation exhibits strong seasonality, soil-living biota in general, and termites in particular, play a vigorous role in moving sediment particles upwards to the surface. This "fountaining" of soil is mainly a response to:

a) Seasonal changes in humidity (which cause fungus-harvesting termites to change vent geometries in order to control temperature and humidity within the mounds)

b) Seasonal changes in groundwater level (with resultant wet-season collapse and dry season re-excavation of tunnels to the water table)
c) Seasonal growth and decay of terrestrial vegetation (termites need earth-covered runways to protect their physiologically primitive bodies from desiccation when foraging in the dry season for lignin-rich plant debris for their fungus gardens)

In some low-gradients parts of the Malawi Rift, runoff has not completely removed the seasonal flux of termite-transported sediment. Consequently, extensive deposits of red muddy unstructured sandstone several metres thick, with successive land surfaces represented by Stone Age artifact horizons and fossil termite mounds, have accumulated.

More usually, the termite mounds and runways of sediment are prone to erosion, and seasonal runoff carries much of this annual increment of bio-transported surficial sediment into the rivers. The sediment fluxes from these areas are therefore to a significant degree initially size-sorted by the soil biota, ensuring that much of the fluvial sediment is mud-rich, and that fluvial sand granulometry is biased towards the finer grain sizes. Such textures are a feature of humid tropical sediments that have historically been ascribed to "tropical weathering". However, soil biota may play an important, if not dominant, role in delivering these sediment characteristics. Fossil termites are known to extend at least into the Early Tertiary, and similar roles may have been played by other soil biota further back in time.

HUMID TROPICAL INUNDATION DEPOSITS: the total area inundated seasonally, on river flood plains or around lakes, can be as large as the total area of river channels, plus 'permanent' swamps and lakes. These inundation deposits include current-rippled and wave-rippled thin sands, with multidirectional transport directions, which are draped by mud and carbonaceous debris as the floods recede. These heterolithic deposits suffer variable levels of bioturbation by aquatic and terrestrial fauna before inundation in the following wet season. The resulting sediments sometimes show relatively thick mud drapes, but otherwise in core closely resemble intertidal mud flat deposits. Palynology or micropalaeontology may be required to confirm a non-marine interpretation.

HUMID TROPICAL FLUVIO-DELTAIC DEPOSITS: Flood phase river mouth-bars develop at points of discharge into the inundation areas. These may be a long way from the end-dry season locations of mouth-bars developed at entry points to permanent lakes and swamps. Locations of fluvial mouth-bars therefore shift laterally, and change in character, on a seasonal basis. Since inundation limits and flood peaks are not usually in phase, and do not occur at the same stage in successive seasons, relatively small scale sand bodies may result. These temporary lacustrine delta mouth-bar accumulations over hundreds to thousands of years may show complex lateral stacking patterns and cross-cutting geometries. These depositional settings are represented in wells by a high proportion of relatively thin sands showing coarsening-upwards log profiles.

HUMID TROPICAL FLUVIAL DEPOSITS: In the basin floor of post-rift sequences, the high rates of sediment flux in relation to tectonic subsidence results in limited accommodation space. Consequently, rapid lateral switching of river courses occurs and, in basins which are not traversed by a major fluvial system (which is the majority), individual sand bodies are relatively small and complex. In these settings dominated by sediment flux, interactions between multiple fluvial sediment input systems with different rates of sediment aggradation, means co-existing braided, anastamosing and meandering styles of channel geometry can occur in close proximity.

HUMID TROPICAL LACUSTRINE SHORELINE DEPOSITS: Deflation of sand from the lake floor during low-stands can result in substantial aeolian sand deposits in back-beach settings, as illustrated around Lake Malawi. These deposits become rapidly modified by vegetation growth and bioturbation. Beach bar systems likewise become rapidly vegetated where not kept clear by human activity. The locations of back-beach aeolian dune systems, and the locations and orientations of major beach bar systems are controlled largely by bathymetry and prevailing wind directions. Bathymetry shows a strong structural control in syn-rift settings.

HUMID TROPICAL ORGANIC-RICH DEPOSITS: The lacustrine source facies developed in deep syn-rift lakes are relatively well characterized and understood. The organic facies of swamps and shallow lakes that are common in pre-rift and post-rift settings in the humid tropics are less well documented.

The open waters of Lake Chilwa, Malawi, show high primary productivity, but the sediments generally contain less than 0.5% organic carbon. This is presumably because the lake benthos includes abundant detritivores. In most years, the lake is fringed by extensive floating mats of vegetation that are thick enough to support temporary huts for fishermen. However, during drier periods, these mats are left stranded on the mud as the lake retreats, and in less than two years of emergence the organic matter is completely destroyed by bacterial decay at these tropical temperatures. Organic muds and peaty accumulations do however persist on the former lake margin during dry periods in the swamps around river mouths and in locations maintained by groundwater discharge. Aquatic macrophytes and freshwater algae both contribute to these swamp deposits, and the balance between these varies spatially. These spatial patterns vary on a historical timescale, so the swamp deposits comprise an intimate mixture of organic facies. If this model applies more generally, as review of similar lakes such as Tonle Sap in Cambodia suggests, then two basic freshwater source facies models may apply in the humid tropics: 1) syn-rift algal-dominated deep lake deposits; 2) mixed macrophyte and algal organic matter swamp deposits.

On balance, it appears that the muds accumulating in major open shallow lakes in the humid tropics may be relatively poor source facies. Consequently, in some cases mixed terrestrial and lacustrine biomarkers in oils in these basins may all be due to swamp deposits, rather than to separate accumulations of lacustrine and coally source facies.

EARTH SYSTEM MODELLING FOR EXPLORATION AND DEVELOPMENT:
It is evident from this brief account that humid tropical depositional systems exhibit distinctive characteristics that carry implications for exploration and development. Consequently, the ability to model humid tropical palaeoclimates, including seasonality in rainfall, runoff, wind strengths and wind directions, would have predictive value. The first stage in making palaeoclimatic models that are accurate enough to be useful to the industry, is to develop high resolution palaeogeographies.

Plate models and palaeogeography: New plate models, which combine both rigid and deformable plates, offer the potential to resolve the evolving complex structural geometries of South East Asia and so set up accurate frameworks for high resolution palaeogeographies. *Climate-ocean models*: These palaeogeographies in turn can provide the inputs for running fully coupled ocean-atmosphere Palaeo-Earth System models, tidal models and ocean wave models. Enormous volumes of model data are generated, but can be distilled down to monthly or seasonal summaries of temperature, rainfall, evaporation, evapotranspiration, runoff, wind directions, wind strengths, ocean temperatures and ocean salinities at multiple levels, ocean current directions, ocean current strengths, and oceanic upwelling. The model can “grow” vegetation in response to climate parameters, with resulting dynamic feedbacks into the modelling. *Tide and wave models:* The tidal models predict tidal range, magnitude of maximum tidal bedstress and direction of maximum tidal bedstress, whilst the wave models, using climate model wind data, deliver significant wave heights, bedstress and direction of wave approach. *Source, reservoir and seal predictions*: These Earth System parameters have been used to derive predictions of fluxes of fluvial and marine sand and mud, evaporite and marine carbonate deposition, together with terrestrial, lacustrine and marine primary productivity. This in turn helps constrain prediction of source, reservoir and seal facies.

RESERVOIR CHARACTERISATION FOR EXPLORATION AND DEVELOPMENT:
Depositional models: It is clear that depositional models appropriate to the humid tropics need to be more fully developed. In part, this reflects the practical difficulties involved in documenting sediment distributions in these heavily vegetated settings. In part, the industry has historically not seen a compelling need to invest in the required research. Now, as the pressure for exploration and development in these inherently complex sedimentary systems increases, it becomes clear that we cannot continue to apply inappropriate analogues and increased effort to document these systems is required. *Reservoir geometric databases*: Continued developments in seismic acquisition and processing, and use of techniques such as spectral decomposition, continue to improve reservoir imaging. However, where seismic imaging is insufficient to define depositional geometries then, provided appropriate analogues are selected, databases of sandbody geometries and volume ranges can help constrain these uncertainties. *Permeability from uncored intervals:* For the sedimentological reasons already outlined, many fluvio-lacustrine basins in the humid tropics contain fine-grained reservoir intervals scattered throughout the basin fill. It is impractical to core such sands extensively, and it is difficult to undertake standard petrographic analysis of ditch cuttings or sidewall cores consistently. This means it is difficult to evaluate permeability without recourse to special logging tools, and in older wells with poor log suites, or in high temperature wells, no assessment of sand permeability in uncored intervals may be possible. High-resolution rock sample scanning research methods, which digitally integrate scanning electron and XRD analyses, are suitable for consistent characterization of fine-grained sandstones. This approach has now been developed into a semi-automatic, and therefore practicable, method for characterizing cuttings and cores.