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Paleodrainage Systems

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You can never step into the same river; for new waters are always flowing on to you.
Heraclitus of Ephesus

1. Introduction

From a geomorphological perspective, river systems can be summarized as a hierarchy of water flux processes occurring in different spatial and temporal scales, organized in a specific geographic setting coupled with a climatic system in a condition of dynamic equilibrium. At the lower and detailed level there is localized turbulent water movement within a channel, which can be described by local flux equations. On a more generic level, other aspects and run off processes must be considered such as the sediment flow dynamic, the regional slope and the wider temporal scale variation (seasonal and multi annual). They can be modeled by open channel hydraulic methods. At a broader level of analysis, one can consider the basin scale associated with the geological conditioning and regional plus global climatological context in long-term processes.

The concept of paleodrainage, as discussed in this chapter, states that large scale changes in fluvial features should be related to wider environmental processes that can alter the very nature of the basin system, thus, despite the breadth of the definitions of concepts such as "paleovalley" and "paleochannel" often attributed to local variations in the drainage system (i.e. seasonal flooding or small scale lateral migration), it is considered that only dynamic processes of effective geographical changes in drainage systems can be included in this range of definitions and related to most common causes:

- Downstream drowning/exposure (base level variation)
- Drying (climate change)
- Shifting (tectonic and morphosedimentary topographic induced processes)

These processes do not necessarily occur as isolated events but rather as a set of environmental changes that include variation of sediment supply, topographic and geological settings, local and regional climate, vegetation coverage, etc. In this regional context, most studies involving paleodrainage are based on two types of analysis: The geomorphological approach based on the response of the landforms to the drainage processes (described in works like Al Sulaimi *et al.* 1997, Simpson, 2004 and Dollar, 2004) and Stratigraphic approaches based on the sedimentary records of the fluvial sequences related to conceptual frameworks such as Quaternary Time Stratigraphy (Wheeler, 1958) and Fluvial Sequence Stratigraphy (Wilgus *et al.* 1988; Strong and Paola, 2008).

Moreover, regardless of methodological differences, the analysis of ancient drainage patterns is almost always related to the tracking of large scale environmental conditions, especially those related to Quaternary glacial cycles and tectonic processes; however, it has also been seen as a means to provide a context for observed historical trends and to predict near future conditions in a changing climate as well as human intervention in land cover scenarios (Bloom & Tronqvst, 2000) and the understanding of the dynamic evolution of natural drainage systems can reveal important insights into the modeling, design and implementation of sustainable methodologies that integrate innovative water resource management and land use planning, which is the main focus of this book.

2. Paleodrainage and environmental changes – why do rivers change?

2.1 Tectonic control and paleodrainage

Tectonic conditioning of drainage changes have been widely described in the literature, and it is usually studied on the regional and continental scale. It can be considered the most dramatic effect not only for conditioning the pattern and texture of the drainage itself but also for determining the characteristics and amount of sediment that is transported to downstream depositional basins and where this sediment is delivered. Uplift, subsidence and faulting, all modify the overall shape of drainage systems, altering parameters such as slope, valley floor and channel gradient. The form and magnitude of these changes will depend on the amount of deformation and the capacity of the channels to adjust to the altered slope (Shumm, 1977; 1985), thus, in order to understand how tectonic evolution impacts drainage development, evolution and preservation, it is necessary to examine the coupling of externally (allogenic) and internally generated (autogenic) forces.

Examples of the characterization of how the tectonic events impacts drainage development - especially associated with orogenic belts - are described in Burbank and Anderson (2001). A good example of such relationships between tectonic processes and drainage changes on a large scale is the case of rivers in Patagonia at the southern end of South America as described in Wilson 1991 and Tankard *et al.* 1995. The rifting process that separated South America and Africa first occurred at the southern part of the continent during the Middle Jurassic, and the development of broad uplifts, rifting and aulacogens were key factors in establishing the drainage patterns. The ancestral flow of the paleo Colorado and Negro rivers, for example, was associated with the Mesozoic paleosurfaces with sources east and north of the Neuquen basin directed to the Pacific Ocean. The Upper Cretaceous Andes arc uplift caused reversion of the slope direction to the southeast, yielding the rivers to flow to the Atlantic, skirting the north side of the Somuncura uplift (Potter, 1997).

The Andean uplift also has controlled the paleo-geographic settings of all drainage in the central and northern cordillera region modifying the position of rivers such as the Orinoco and Magdelena at northwestern part of South America. As described in Horn *et al.* 1995 and Diaz de Gamero, 1996, during the Middle Eocen, the Orinoco River had been flowing south-north, draining the Central Cordillera of Colombia and the Guayana Highlands, with its mouth associated with the Lake Maracaibo and Caribbean Sea. After the Late Miocene period, the Andes attained their present configuration following the Eastern Cordillera uplift and the southwestern end of the Merida Andes deformation shifted the course of the river, deflecting it to a west-east direction. The eastern and central Cordillera uplift also controlled the paleo-Amazon River, which was connected to the Paleo-Orinoco until the mid Miocene period. The final breakthrough of the Amazon River towards its modern course occurred with the final uplift of the central Andean cordillera, related to the rise of the Purus Arch (Gregory-Wodzicky, 2000; Figueredo *et al.*, 2009) (Figure 1).

Tectonic processes have also controlled drainage evolution and basin infill trends in all active zones in the world. In the Himalayas, the Orogen began forming roughly 50 million years ago when India collided with the Asian continent producing complex relationships between regional metamorphism, anatexis, thrust faulting and normal faulting (Hodges, 2000). The establishment of the drainage systems and the evolutionary history of the fluvial network were controlled by this complex scenario characterized by both local and regional structures with multiple phases of deformation and shaped by active erosional dissection. Studies such as those done by Brookfield (1998), Zeitler *et al*, (2001), Najman *et al*. (2003), Clift and Blusztajn (2005), among others, affirmed that the transpressional tectonics across the Himalayan arc have produced large variations in fluvial morphodynamic processes in rivers such as the Indus, Kunar, Marsyangdi and Ganges. Most of these changes as described in Clift *et al.* (2006) can be related to capture/reversal processes.

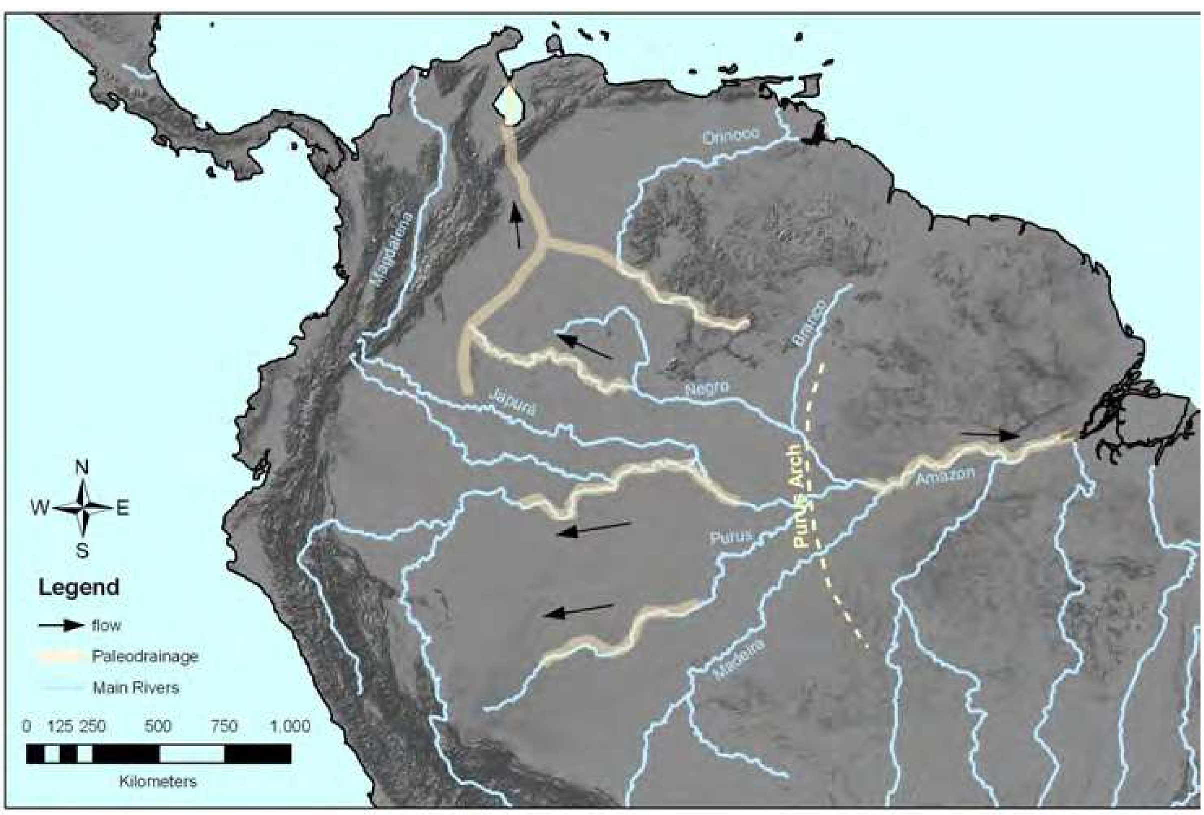

Fig. 1. Drainage distribution of Northern and Central areas of South America indicating the Amazon/Andes paleodrainage system (and flow direction) during Oligocene (modified after Potter, 1997 and Horn *et al.* 2010).

Furthermore, the climatic and erosional processes related to such uplifts, which have determined the resultant landscape structure, are as important as the direct upward topographic responses to tectonic forces. Finnegan *et al*. (2008) analyzing the balance between uplift of the Namche Barwa massif in Tibet related to the Yarlung Tsangpo–

Brahmaputra River system, concluded that the regional denudation driven by extreme efficient river incision, removes a large quantity of sediments yielding to a local relief producing erosional and thermo-mechanical coupling in an active orogen, thrusting Namche Barwa-Gyala Peri above the surrounding landscape in a process of "tectonic aneurysm" (Koons *et al.* 2002 and Simpson, 2004).

The tectonic dynamics can also affect large-scale drainage patterns through volcanism and distention processes in divergent plates. In the African continent there are at least two examples of rivers indicating complex histories involving shifts in the nature of their catchments and courses, associated with volcanism and rifting process. The Nile may be one of the most remarkable examples of drainage evolution in response to non-orogenic tectonic deformation. The Nile evolution model described by Sahin (1985), Foucault and Stanley (1989); Issawi and McCauley (1992) and Goudie (2004), details five phases since the late Eocene.

The first phase (called the "Gilf system" - Eocene) was marked by the presence of a set of parallel north flowing drainages occupying most of northeastern Africa and the present Nile Basin position fed by streams originating from eastern highlands (Red Sea area). The second Stage (Qena system - Miocene) was marked by intense tectonic activity followed by the reversion of the drainages taking up a southward position as well as establishing an immense river flowing south towards Aswan and the Sudan. The third stage (the Nile system – Late Miocene) was marked by a dramatic drop of the base level of the Mediterranean Sea (associated with the closure of the Straits of Gibraltar and the Messien Event – Gautier *et al.*, 1994) producing intense erosional activity forming gorges and canyons (designated as Eonile). As a result of such shifts, the Eonile took a northerly course. The fourth phase (Pliocene flooding), in the early Pliocene, the sea level rose at least 125 m so that an estuary or ria extended more than 900 km inland, reaching Aswan. After the Pleistocene, the Nile has been submitted to constant changes due to climate and hydrological regimes (detailed in Foucault and Stanley, 1985; Coutelier and Stanley, 1997).

The other example of a paleodrainage system controlled by distensive tectonics is the Zambezi River. The longitudinal profile of the Zambezi River forms two concave-upward sections, with their boundary at Victoria Falls, and there are studies suggesting that these sections were disconnected fluvial systems only joined together after the late Quaternary (Goudie, 2004; Nugent, 1990). The paleo-Zambezi was connected to both the Limpopo and Luangwa River system and took its present configuration, probably after the Pliocene with the uplift of the Makagdikgadi Basin along the "Kalahari Zimbabwe axis". The new position of the Middle Zambezi permitted the capturing of east and northeast tributaries such as the Kafue and Luangwa (Thomas and Shaw, 1991) (Figure 2).

The evolutionary history of the Congo River is also linked to the tectonic processes related to south-central Africa vertical crust movements. Stankiewicz & Dewit (2006) suggested that the Congo drained into the Indian Ocean until the uplift of East African Highlands in the Oligocene or Eocene (30– 40 Ma). The Congo then became a landlocked basin, until it was captured during the Miocene by a river system causing it to drain into the Atlantic.

Examples of drainage modifications in catchments affected by the formation and erosion of volcanoes can be found in several scales, from regional drainage system displacements associated with major volcanic structures (such as *Serra Geral*/Etendeka and Deccan) to

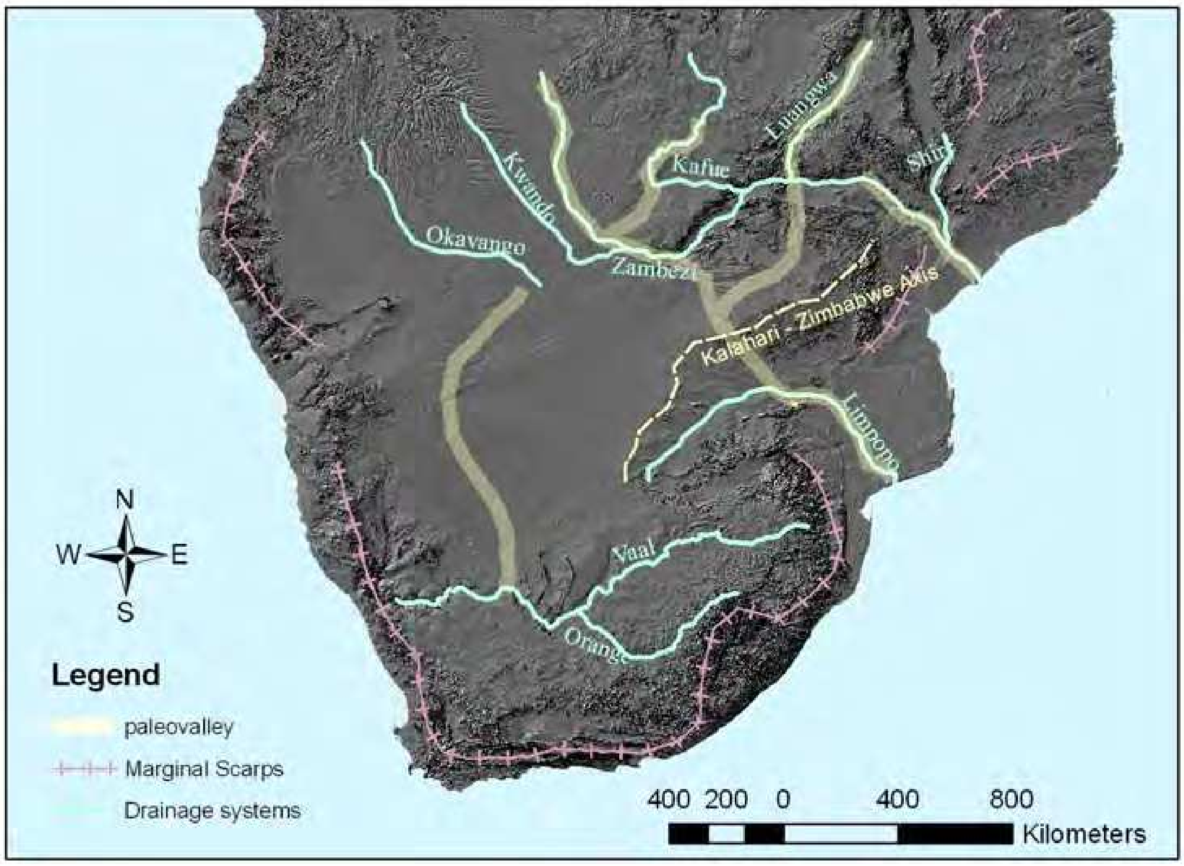

Fig. 2. Drainage distribution of Southern Africa with the paleodrainage prior to the union of the middle and upper Zambezi in the early Pleistocene (modified after Thomas and Shaw, 1991 and Goudie, 2005).

localized events displacing and rearranging local streams. Oilier (1995), describes the relationship between directions of rivers in southeastern Australia (e.g. Hunter, Lachlan and Murrumbidgee) which reversed courses due to an Eocene/ early Oligocene Volcanism effect. On a more localized scale, Branca and Ferrara, 2001, mapped the ancient valley of the Alcantara and S. Paolo Rivers, below the northern flank of Mt Etna. The paleo-valley was filled by lava flow and volcano-sedimentary debris during several events starting from 170,000 years B.P. until 20,000 years B.P.

2.2 Climatic and hydrologic changes

The first empirical works relating environmental changes with variations in fluvial patterns always attempted to establish a direct correlation between climate changes and the settlement of morphosedimentary processes in drainage systems. Penk (1927) proposed links between incision and deposition patterns of fluvial canals in the Danube River region with glacial climatic cycles, which eventually became one of the main geo-indicators for the existence of glacial cycles. According to the authors, the sequence of terraces formed in fluvial plains would have resulted from alternating glacial (aggradation process) and interglacial (incision process) periods, forming the sequence of terraces that indicate specific environmental conditions. Davis, 1896, recognized the relationship between river displacement and climatic changes studying the Moselle River (northern France).

Several models involving the relationship between drainage system patterns and climate change have been proposed throughout the 20th century incorporating concepts such as hydraulic geometry (e.g. Leopold and Maddock, 1956), fluvial facies and sequence stratigraphy (e.g. Wescot, 1993) along with dating techniques (e.g. Sanderson *et al*., 2003; Zhang *et al*., 2003, Wallbrink *et al*., 2002). In recent decades, multidisciplinary studies have proposed a more holistic approach to integrate climate change and paleodrainage pattern response affected by multiple drivers of varying spatial and temporal dominance and complexity (Knox, 1993, Ely *et al*. 1993; Gibbard and Lewin, 2002; Andres *et al*. 2002; Goodbred, 2003, Vandenberghe, 2003).

The control of glacial cycles in a fluvial system occurs at two different levels: Upstream Controls associated with Continental Interiors and Downstream Control in continental margins. At the upstream level, the relationship between variation of climatic regime and fluvial morphodynamics is usually associated with hydrological changes, on a broader scale, as a regional manifestation of a global pattern of atmospheric circulation or internal dynamics, with feedback mechanisms, while in downstream systems, the base level variations (i.e. sea-level) are the underlying drivers of erosion and incision processes.

The variations of drainage patterns in upstream systems relate to climate changes, and their association with hydrologic processes has been the focus of investigations since the publication of the earliest works on fluvial geomorphology. Patterns of marginal terrace construction in glacial periods (in contrast to incision processes in interglacial periods driven by changes in hydrological and sedimentary processes) also can produce more dramatic landforms. The climatic conditions not only affect the hydrologic regime (i.e. the flow increase or decrease in stream discharge) but also act on factors such as the vegetation coverage, weathering processes (which determines the sediment supply to the system) and the role of the sediment transport agents.

The clearest examples of geographical changes in drainage landform patterns controlled by climatic agents are the drying and desertification processes, associated with an increasingly arid climate condition. Most of the world's deserts present clear signals of paleo drainage systems related to humid periods in the past. The Sahara paleo drainage, as an example, has been investigated by McCauley *et al*., 1986; Pachur and Kroepelin, 1987, Burke *et al*. 1989; Robinson *et al*. 2006; Ghoneim and El-Baz, 2007 among others. Beneath the mobile Eolian sand sheet, sand covers several paleo basins and channels varying from a few to hundreds of meters in width. Most of these systems have been established during the Messinian salinity crisis period (late Miocene, 5–6Ma - previously discussed) when the incision activity reached its maximum, followed by recurring activity during wet periods in the Quaternary. Paiollou *et al*. 2009, using radar images and digital terrain modeling, mapped the Kufrah and Sirt basins (Southern Libya) and concluded that the ancient Kufrah/Wadi Sahabi Rivers would have been active during wet periods (until the Holocene) showing diverse depth levels of incised channels, moreover, during the Eemian interglacial maximum, 125 k.y. ago. The Kufrah River system would have been more than 1200 km-long, comparable in size to the Egyptian Nile.

Studies showing direct links between climatic data and geomorphological analysis of paleodrainage systems in semi arid as well as desert environments are relatively rare[1]

[1] Exceptions can be found in works related to karst systems (e.g. Frumkin *et al* 1998; Defni *et al* 2010).

(Maizels, 1990; Langping *et al*. 2009) since the cause-effect relationships between long term rainfall and morphodynamic of paleodrainages are not always direct. In fact, recent studies have mapped near-surface paleochannels in Namibia (Lancaster *et al,* 2000; Lancaster, 2002) indicating that during the late Quaternary, there was no significant changes in precipitation in the desert itself, but there were considerable variations with more frequent and/or longer duration discharges in ephemeral rivers, suggesting an increase of precipitation only in the upper part of the basin.

It is not only deep variations in climatologic regimes, leading to desertification and drastic opposite states of wet and dry periods, that can be responsible for considerable changes within a drainage system. In some cases, smaller scale/higher frequency variations in factors such as sediment supply, vegetation coverage or catastrophic floods can provoke considerable displacements and shifts in the fluvial systems, with or without the presence of tectonic amplification. The concepts of “River Metamorphosis” (Schumm, 1967 and 1985), “Avulsion” and “Cutoff” (Allen, 1965) and “stream piracy” (Pederson, 2001) have been proposed to describe such processes of channel migration into the watershed and have been widely studied as they are often associated with changes in climatic conditions (e.g. Hocke 1977; Werritty and Ferguson , 1980; Ashworth and Ferguson, 1986; Bridge, 2003).

Knox, (2000) in an extensive study on the Mississippi and Colorado River Valley and tributaries, described how magnitude and recurrence of paleofloods are linked to major climatic events during the Holocene and suggests that, even relatively modest, changes in climate can cause important flood episodes, and these changes in morphodynamic processes have often occurred abruptly at various time scales from decadal to millennial and even longer. Similar results were described by Benito *et al.* (2003) for the Iberian Peninsula, St.Laurent *et al*. (2001) Canada, Sih et al. (1985) and China among others.

Despite that fluvial system adjustments to new climatic and hydrological regimes are able to produce major responses at upstream levels, the effects of base level control in downstream levels (in response to Glacio-eustatic fluctuations) effectively can produce clear paleodrainage records in continental margins and coastal plains, and the significance of these characteristics can be very elucidating for understanding geomorphic processes associated with sea level changes. The paleodrainage characteristics is one of the main geoindicators of continental margin evolution over the Glacial periods when most of the world´s shelves were exposed to sub aerial incision during relative sea level low-stands, and the cross-shelf valleys were directly connected to the continental slope and deep marine environments. From a sequence stratigraphy point of view (see Van Wagoner *et al*. 1990), an understanding of how, when, and where incised valleys are excavated in response to sea level variations remains a topic of considerable interest since the basal surface of paleovalley fills is commonly taken to define the sequence boundary, the most commonly used bounding surface for the identification of allostratigraphic units (Tronqvist *et al.* 2005).

Models developed by Koss *et al.* (1994), Ashley and Sheridan (1994), Meijer (2001); Gutierrez *et al*. (2003), Weber *et al*. (2004) and Hori *et al.* (2002) Strong and Paola (2006) suggest that, despite continental shelves, paleovalleys can be correlated with the paleo-hydrological regime in which the channel was formed; they also can be associated with submerging processes in the incised valleys during marine transgressions, reflecting the interaction between the autogenic and allogenic forcings. Still, the relative and absolute effect of these mechanisms remains unclear (Wellner and Bartek, 2003).

A quite thorough review on the fluvial systems response to sea level variations can be found in Bloom and Tronquvist, 2000: According to the authors, fluvial responses to climate and sea-level change can be disaggregated into stratigraphic, morphological and sedimentological components: The stratigraphic responses are produced by aggradation due to increasing accumulation space, degradation as accumulation space decreases and lateral migration when there is no change in accumulation space and the fluvial systems in fluvial systems in subsiding basins. These are characterized by long-term net aggradation, punctuated by relatively short periods (10^3 - 10^4 years) of incision and/or lateral migration (in opposition to typical upstream valleys). Morphological responses reflect changes in channel system geometry and sedimentological responses are associated with changes along with the spatial distribution of depositional environments and proprieties of lithofacies.

3. Method of analysis – tracking ancient rivers

Paleodrainage systems, as previously mentioned, can be a powerful tool for modeling paleo-environmental scenarios and understanding the geological and climatic dynamics in time scales that ranges from seasons to millions of years, even though the identification and characterization of such features is usually indirect and quite often requiring a detailed process of analysis and integration of data from multiple sources. Perhaps the most comprehensive review of general principles on this topic is provided by Andersen (1962) who previously recognized the main geological aspects of mapping paleodrainage distribution maps. According to the author,

" […] paleodrainage maps can be constructed in several ways: 1) by making a structural contour map of the erosion surface at the base of the valley fill; 2) by making a number of stratigraphic cross-sections which intersect the valley trends - valley axes are approximated by connecting consecutive valley low-points which have been plotted on a map; 3) by making a paleogeologic map of the surface at the base of the valley-fill - valley axes are drawn in the middle of the areas where the oldest rocks are represented; 4) by isopaching the interval between the valley floor and some datum- valley axes are where the valley floor is farthest from or closest to the datum depending on whether the datum is above or below the valley floor; and 3) by making an isopach# map of the valley-fill - valley axes are where the fill is the thickest. Knowledge of paleodrainage patterns in a given area allows the geologist to conclude the direction of paleoslope, local paleotopography, the approximate direction of the source area from the study area, the character of the surface into which the valleys were cut, and whether or not there was any structural activity in the study area during the time of valley carving."*

The development of new methods in geomorphology to record and quantify past and recent geomorphic processes allied with the implementation of techniques of geoprocessing and Geographic Information Systems have permitted increased accuracy in reconstructions of past environments. This new "geomorphological" approach has also provided valuable insights into the formation and evolution of fluvial systems. Mapping topographical attributes, for example, can still be the simplest and most intuitive method to recognize some aspects of the ancient fluvial geomorphology and usually can reveal several characteristics of the fluvial system. In practice, however, the original local landform is rarely preserved after morphodynamic processes that caused the changes in the fluvial patterns, so the use of elevation data (obtained from different sources) should be accompanied by further geophysical investigations, in order to track aspects of the original landform configuration.

Examples of using of integrated methods based on multi parameter investigation of paleodrainage can be related to drying and desertification processes in which the original landform still lies only a few meters above the sand sheet, still remaining recognizable. Ghoneim & Elbaz (2007), based on SRTM elevation data obtained on a near-global scale (3 arcsec resolution) in combination with Radarsat-1 Synthetic Aperture Radar Images and Landsat TM satellite images, made a complete paleoenvironmental analysis of the Tushka basin between Egypt and Sudan (figure 3). Similar methods were used by Sultan *et al* (2004), Marinangeli (2005) Gaber *et al.* (2008) Blumberg *et al.*, (2004); Griffin, (2006); Pachur and Altmann, (2006) demonstrating good potential for recognizing topographic patterns of paleodrainage in semi arid or arid areas.

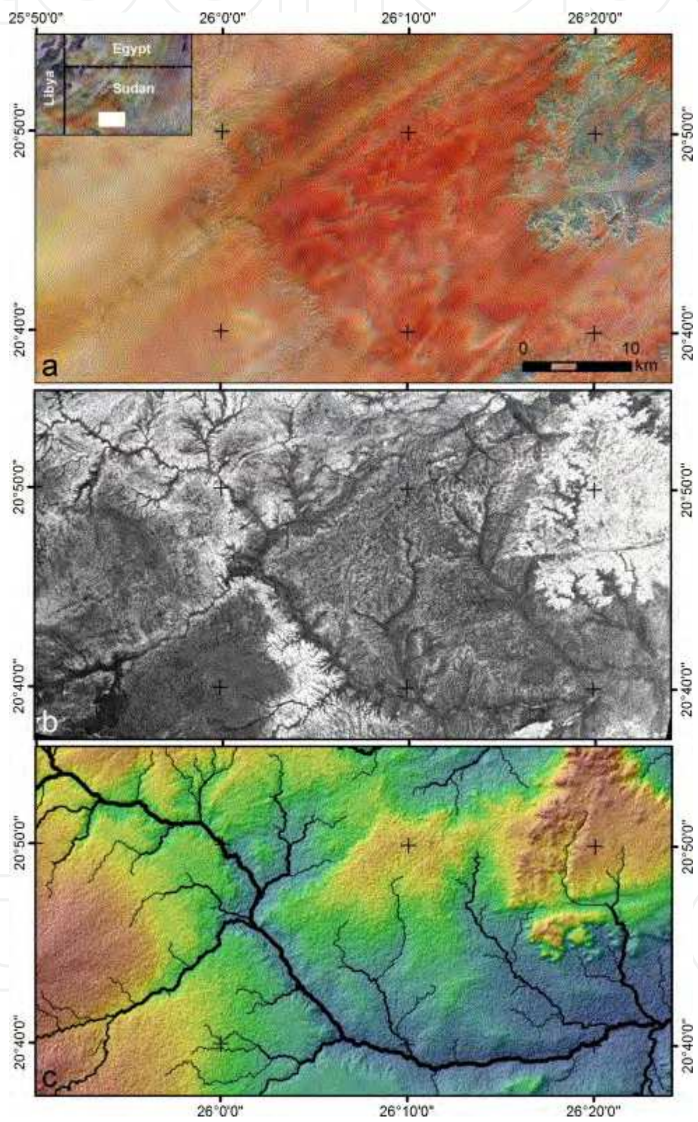

Fig. 3. (a) typical example of multi data INTEGRATED to characterize paleodrainage networks - Landsat ETM+ color composite (bands 7, 4, 2) covering an area in NW Sudan - showing the dominance of surface sand deposits. (b) Radarsat-1 image showing a distinct subsurface drainage network trending eastward; note the absence of the surface sand deposits. (c) The SRTM DEM (90 m) with the delineated drainage network overlain; note the good correspondence between the SRTM-generated channels and the Radarsat-1 subsurface channels (after Ghoneim & Elbaz, 2007).

Furthermore, some of the most interesting studies in paleodrainage recognition have been developed by applying topographical analysis in conjunction with spectral information in tropical/equatorial forests. Haywakawa *et al*. (2010) has analyzed the ancient drainage complex of the Madeira River, one of the main Amazon tributaries and was able to delineate a complex system of abandoned channels due to avulsion processes during the Late Pleistocene- Holocene, despite the area being covered by dense forests (figure 4). Rossetti (2010), after analyzing topographic and spectral data has also produced satisfactory results in understanding the resulting drainage rearrangement in the Amazonian lowlands.

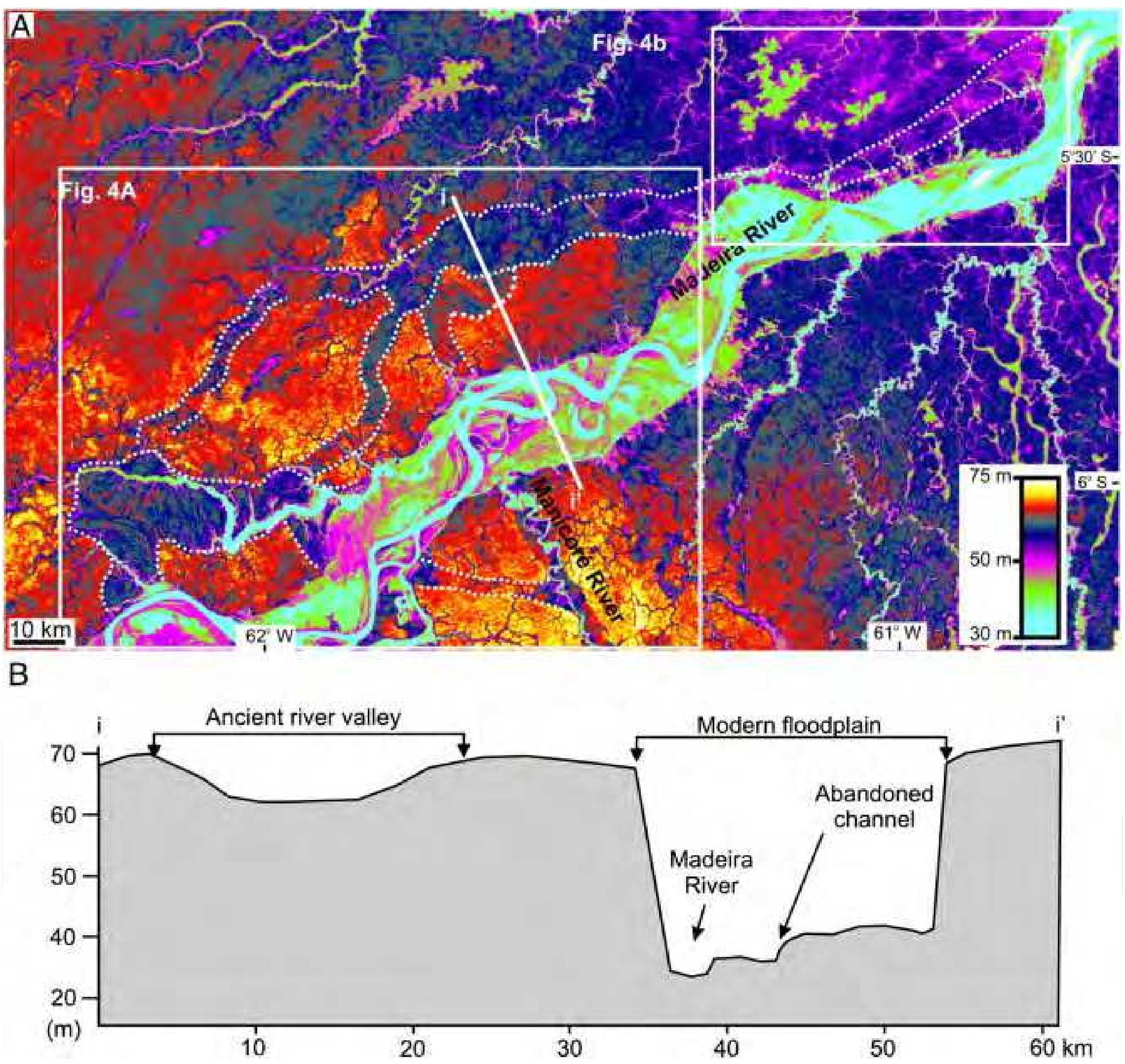

Fig. 4. DEM-SRTM with the regional view of the study area and the location of the paleodrainage network (dashed lines) detected in the Madeira-Manicoré Rivers. B) Topograhic profile (i–i′) derived from DEM-SRTM. Observe that paleodrainage occurs in an area topographically higher than the modern Madeira valley (after Haywakawa *et al.* 2010).

In downstream systems, the subsurface mapping for locating and analyzing cut and fill structures associated with buried incised channels across continental shelves is probably one of the most widespread applications involving paleodrainage studies. Several studies have considered these factors as indicators of the paleogeography of the subaerial surface as well as the fluvial and hydrological regime during regressive events (see Reynaud *et al.*, 1999; Lericolais *et al*., 2003; Tesson *et al*., 2005; Meijer, 2002).

Despite the focus on direct analysis of channel incision surfaces and their relation to quaternary stratigraphy based on high resolution seismic data (e.g. Thorne, 1994; Lericolais *et al*., 2001; Hori *et al*., 2002; Nordfjord *et al*. 2005, Ashley and Sheridan, 1994; Zaitlin *et al*., 1994), along with the fact that they are covered by marine sediments deposited during and after rises in sea levels (Correa, 1996; Harris and O'Brien, 1996; Collina-Girard, 1999; Abreu and Cagliari, 2005; Finkl *et al*., 2005) and the small number of studies characterizing the topographic expression of the paleo-drainage registers (Strong and Paola, 2008;), it is still possible to identify and classify the main paleo-valley axis in the surface topography.

Conti and Furtado 2009, having studied the paleodrainage registers of the southeastern Brazilian continental shelf, observed that the paleo-valley features present diverse topographical expressions and are related differently to the drainage system that generated them. Some of those identified by the Digital Terrain Model (DEM) were quite conspicuous and easily detected, while others could only be distinguished by using enhanced filters on the topography DEM; however, there is no direct relation between the size and dimension of the paleo-valleys and the shape, form, outflow or basin characteristics of the modern rivers.

A particularly interesting example of how the use of multi data in a Geographic Information System framework proved to be valuable in understanding the paleo drainage records is the case of the downstream of Ribeira de Iguape River – RIR (southeastern São Paulo state – Brazil). The analysis of remote sensing images (Landsat TM), in particular near infrared bands of the coastal plain of the river, reveal areas with high wetness index values indicating an abandoned channel feature with a divergent orientation in relation to the modern RIR position (figure 4a). A bathymetry digital terrain model (DTM) of the adjacent Continental Shelf mapped two channel-like structures in submarine topography; one clearly related to the present estuary of the RIR and another, more than 15 km southward, apparently connected to the paleochannel have been identified on satellite images (figure 4b). High-resolution seismic profiling data on the supposed point of convergence of these two features (satellite images and DTM) revealed the presence of a prominent cut and fill structure indicative of channel incision (figure 4c). The body of evidence points to two distinct positions of the RIR during two low-stand periods: one associated with the actual position of the river at the north and another one, probably older, diverging more than 30 km from the present estuary, headed seaward in a mostly direct path, forming the paleovalley features in the coastal plain and on the continental shelf.

Incised valleys are also often associated with large-scale sediment bypass zones that feed downdip into large sandy deltas, so the stratigraphic characterizing of these features can provide reliable information on the general characteristics of a paleofluvial regime (Dalrymple *et al*., 1994). Different sedimentation models based on the fluvial and marine deposition during relative rises and falls of sea level can be constructed based on direct (biostratigraphic, isotopic, and geochemistry data) and indirect (seismic data) analysis of such submarine fans. Examples in the Amazon (Mikkelsen *et al.* 1997 and Figueredo *et al.*

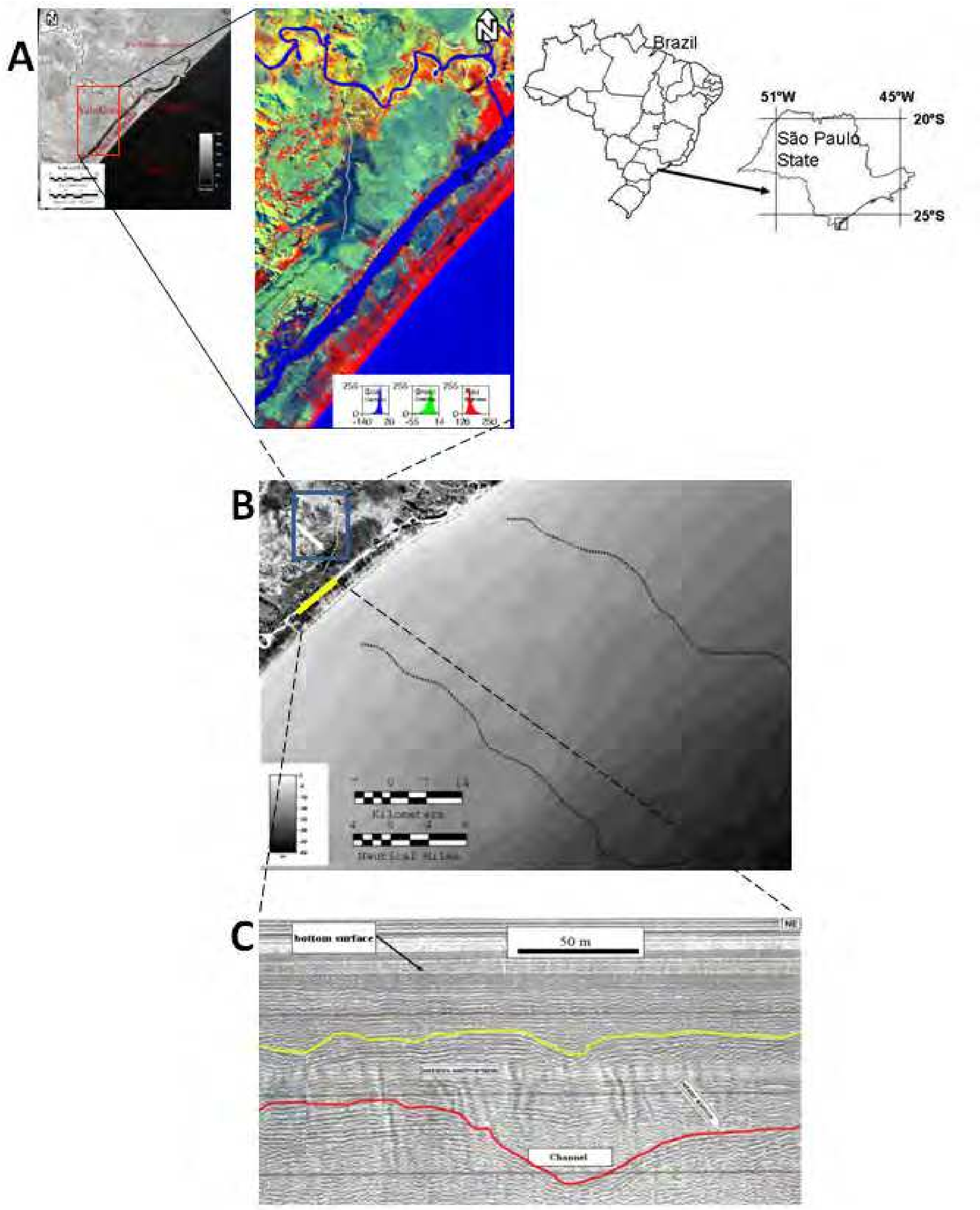

Fig. 5. Indicators of the paleo Ribeira de Iguape River – Southeastern Brazil. (a) Position of a wet lowlands indicated by vegetation indices from Landsat Images. (b) Digital Terrain Model from the continental shelf bathymetry indicating the presence of two paleovalleys (c) cut and fill structure in a high resolution seismic profile.

2009), Indus (Qayyum *et al.* 1997), Danube (Panin *et al.* 1998), and Pearl River (Pang *et al.* 2006) among others, have proven that the sediment load variability respond not only to climate changes that affect the river discharges but also to processes within the basin such as tectonic and autogenic processes.

Recent improvements in genetic analysis involving biogeography paleoenvironmental reconstructions have been making important contributions to the understanding of the history of the ancient drainage systems. Freshwater fish, in particular, have indicated strong relationships between historical river connections and phylogeographic patterns since changes in fluvial patterns might have been the source of isolation and divergence for aquatic species, forming barriers to gene flow. In this context, a large number of studies have been suggesting even the influence of the paleodrainage on species evolution and vicariance processes as well as the other way around, resorting to biodiversity in order to reconstruct fluvial paleoenvironments (see Waters, 2001, Cook *et al.*, 2006; Ribeiro, 2006; Burridge *et al.* 2007; Flinstone *et al.* 2007).

4. Final remarks

There are several open questions involving the evolution of drainage in response to long-term environmental changes. Some of these questions have been debated since the mid 20th century after the publication of major quantitative studies on dynamic fluvial geomorphology (e.g. Horton, 1945; Strahler, 1952; Shreve, 1969; Schumm, 1972; 1977 and 1987). Perhaps one of the most intriguing questions related to the evolution of fluvial systems is the relationship with base level low-stands. The models for incised valleys assume that relative sea-level fall produces an upstream propagating wave of rejuvenation, but how far reaching and how impacting are these processes, is still a matter for discussion. Other key aspects of paleohydrological and paleoenvironmental sciences remains unclear and uncertain, for example, the role of feedback effects on the climatic forcing (such as peak precipitation) to indirect (such as permafrost melting) and partial forcing (such as vegetation suppression) on the evolution of fluvial systems (Vandenberghe, 2003) and the temporal scales, time lapses and coupling of different stages of the geomorphic processes (Harvey, A.M., 2002). In fact, most of the models for reconstructing the morphology and hydrology dynamics in response to climate change (either in continental upstream or continental shelves downstreams) are quite incomplete in delivering quantitative descriptions and predictions, therefore, the development of integrated frameworks is fundamental to understanding such relationships.

Considering further development of global warming, intense urbanization, deforestation and need for hydroelectric energy, there is no option for the near future, but to develop integrated and multidisciplinary research focused on the study of geomorphological and geological mechanisms of evolution of landscapes, in particular for fluvial systems, and it is very clear that the same uncertainties and achievements can be broadly applied to artificial drainage systems, independent of the temporal and spatial scale. Today, at least one billion people live along or near rivers and channels worldwide (Palmer *et al.* 2008) and only a complete synergy between observation and understanding of empirical evidence of paleodrainages on the local and general scale and theoretical models based on rigorous physical assumptions will provide a robust scientific body of knowledge capable of improving the accuracy and reliability of broader and better-integrated models and theories increasing their usability for forecasting, simulating, and planning proposals.

5. Acknowledgments

The author would also like to acknowledge the financial support of FAPESP (Fundação de Amparo a Pesquisa do Estado de São Paulo) – Grant: 2011/20563-4

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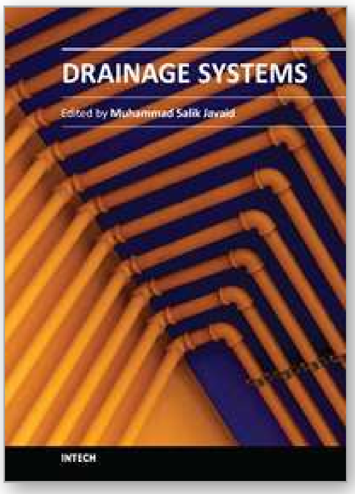

Drainage Systems

Edited by Prof. Muhammad Salik Javaid

ISBN 978-953-51-0243-4
Hard cover, 240 pages
Publisher InTech
Published online 07, March, 2012
Published in print edition March, 2012

The subject of 'drainage: draining the water off' is as important as 'irrigation: application of water', if not more. 'Drainage' has a deep impact on food security, agricultural activity, hygiene and sanitation, municipal usage, land reclamation and usage, flood and debris flow control, hydrological disaster management, ecological and environmental balance, and water resource management. 'Drainage Systems' provides the reader with a tri-dimensional expose of drainage in terms of sustainable systems, surface drainage and subsurface drainage. Ten eminent authors and their colleagues with varied technical backgrounds and experiences from around the world have dealt with extensive range of issues concerning the drainage phenomenon. Field engineers, hydrologists, academics and graduate students will find this book equally benefitting.

How to reference

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Luis Américo Conti (2012). Paleodrainage Systems, Drainage Systems, Prof. Muhammad Salik Javaid (Ed.), ISBN: 978-953-51-0243-4, InTech, Available from: http://www.intechopen.com/books/drainage-systems/-paleodrainage-systems

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