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Large-scale drainage capture and surface uplift in eastern Tibet–SW China before 24 Ma inferred from sediments of the Hanoi Basin, Vietnam

Peter D. Clift,[1,2] Jerzy Blusztajn,[3] and Nguyen Anh Duc [4]

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[1] Current models of drainage evolution suggest that the non-dendritic patterns seen in rivers in SE Asia reflect progressive capture of headwaters away from the Red River during and as a result of surface uplift of Eastern Asia. Mass balancing of eroded and deposited rock volumes demonstrates that the Red River catchment must have been much larger in the past. In addition, the Nd isotope composition of sediments from the Hanoi Basin, Vietnam, interpreted as paleo-Red River sediments, shows rapid change during the Oligocene, before ~24 Ma. We interpret this change to reflect large-scale drainage capture away from the Red River, possibly involving loss of the middle Yangtze River. Reorganization was triggered by regional tilting of the region towards the east. This study constrains initial surface uplift in eastern Tibet and southwestern China to be no later than 24 Ma, well before major surface uplift and gorge incision after 13 Ma. **Citation:** Clift, P. D., J. Blusztajn, and A. D. Nguyen (2006), Large-scale drainage capture and surface uplift in eastern Tibet–SW China before 24 Ma inferred from sediments of the Hanoi Basin, Vietnam, *Geophys. Res. Lett.*, *33*, L19403, doi:10.1029/2006GL027772.

1. Introduction

[2] Constraining the history of surface uplift in eastern Tibet and surrounding regions of southwest China is important to understanding the overall history of surface uplift and strain accommodation following the India-Asia collision. Determining the patterns of surface uplift is important to resolving between competing models of strain accommodation in the India-Asia collision zone, which remain divided between those favoring horizontal compression of a more plastic crust [e.g., *England and Houseman*, 1989] and those that invoke lateral extrusion of rigid crustal blocks along strike-slip faults [e.g., *Peltzer and Tapponnier*, 1988]. Progress is being made in quantifying the timing of major uplift through application of paleobotanical [e.g., *Spicer et al.*, 2003] and stable isotope methods [e.g. *Garzione et al.*, 2000], yet the start of uplift is less well constrained.

[3] The evolution of drainage patterns can be used to understand how topography has evolved because rivers are sensitive to changes in the regional gradient. It has been suggested that the unusual, non-dendritic drainage patterns recognized in some river systems in eastern Tibet, southwest China and parts of Indochina represent remnants of an ancestral Red River system that dominated the area prior to Tibetan uplift (Figure 1b) [e.g., *Brookfield*, 1998; *Clark et al.*, 2004]. This river system is proposed to have been disrupted by a series of drainage capture events between the major rivers that flow from eastern Tibet. Capture is envisaged as being caused by regional surface uplift that changed the slope and elevation of Southeast Asia over a wide region, diverting or even reversing river flow directions. Large-scale changes in river discharge must have had major impacts on the paleoceanography of the Asian marginal seas, as well as on the development of delta systems, yet presently these processes are unconstrained in East Asia.

2. Sedimentary Records of Capture

[4] In this study we use the sedimentary record of the Hanoi Basin, Vietnam (Figure 1a), to constrain for the first time the age of major drainage capture in the Red River system, and by inference the start of surface uplift in Southeast Asia. The approach is based on the assumption that as major tributaries are gained or lost from any given river system the composition and volume of the sediment reaching the delta will change as geochemically distinctive sources are removed or added to the source regions. The use of marine sediments to date drainage capture events has recently been demonstrated in the Indus River [*Clift and Blusztajn*, 2005] and is based on the contrasting geological histories of the different source regions supplying sediment to the main river.

[5] Comparison of the volumes of sediment in the basins that are now fed by the Red River and the volume of rock eroded from the modern catchment provides a first order test of the drainage capture hypothesis. Seismically defined sediment volumes corrected for burial compaction and loss of porosity have been used to determine volumes of eroded rock in the Song Hong-Yinggehai and related basins (Figure 1a) [*Clift and Sun*, 2006]. Interpreted seismic reflection profiles were converted to eroded rock volumes by converting the sections from a vertical time axis into depth using stacking velocities. Of all stages in the sediment budget estimation this process was the most prone to error and results in uncertainties of up to 20% due to uncertainties in the velocity-depth conversion. Age control is provided by nannofossil biostratigraphy and is typical of the fairly low resolution used for industrial purposes, being limited to epoch and sub-epoch level. Dating of sequences was done using cuttings, and while this can introduce a vertical uncertainty to the age picks (~10 m) this is generally small

[1]School of Geosciences, University of Aberdeen, Aberdeen, UK.
[2]Visiting professor at South China Sea Institute of Oceanology, Chinese Academy of Sciences, Guangzhou, China.
[3]Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA.
[4]Vietnam Petroleum Institute, Hanoi, Vietnam.

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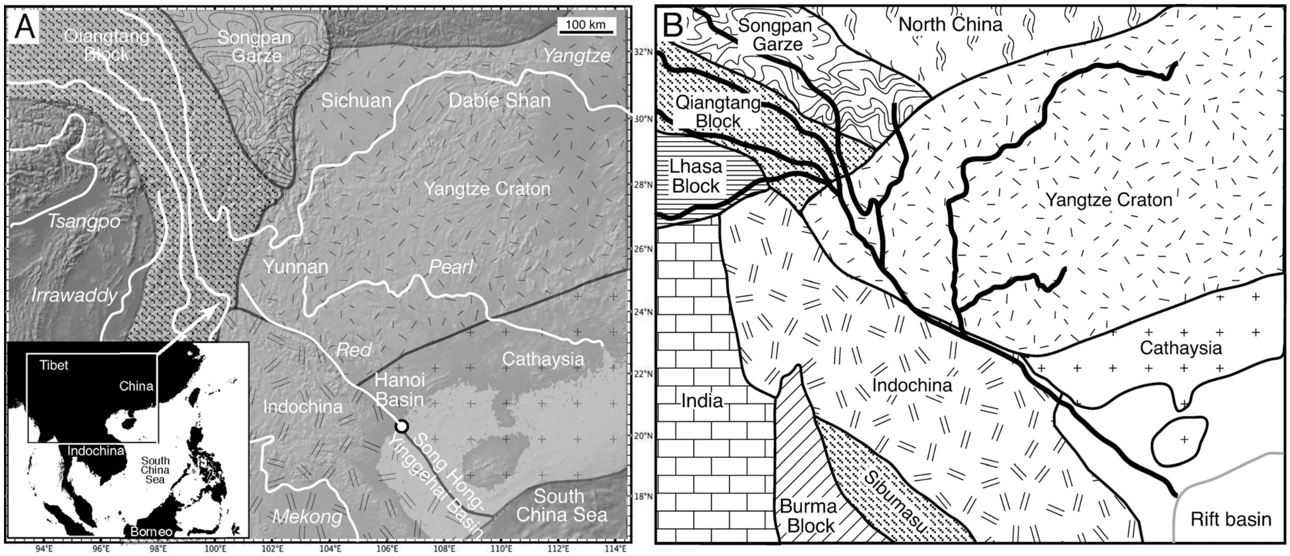

Figure 1. (a) Map of East Asia showing the major river systems and the location of the borehole (white spot) from which samples were taken together with the outlines of the major tectonic blocks that form sediment sources in East Asia [after *Metcalfe*, 1996]. (b) Map showing proposed original drainage pattern for the paleo-Red River, with the middle Yangtze draining to the southwest into the South China Sea. Reconstruction taken from *Hall* [2002]. Insert map shows location of region within East Asia.

compared to the vertical resolution of the seismic data and the great thicknesses of the sedimentary packages themselves.

[6] Erosion onshore can be measured using a range of thermochronometers to constrain timing and depth of erosion. When coupled with outcrop area these data can be used to estimate volumes of eroded rock (Table S1 in auxiliary material[1]). Figure 2 shows the extent of the metamorphic massifs (Song Chay, Ailao Shan, Day Niu Con Voi) whose exhumation is constrained by thermochronometry. In this study we assume a geothermal gradient of 30°C/km, although this may have been somewhat higher, at least locally, along the Red River Fault Zone. Erosion uncertainties are estimated at ±15% as a result. In addition, erosion is generated by plateau uplift and gorge incision. We estimate the volume of rock removed by this process by treating the surface of Tibet as an uplifted peneplain into which gorges have been incised (Figure 2) [e.g., *Clark et al.*, 2005]. Modern digital topographic data makes estimation of the volumes missing from the gorges in the Red River basin relatively straightforward and with low uncertainty (±10%). Geomorphologic and thermochronologic data suggests that most of the major incision in the modern Red River basin is Pliocene or younger in age [*Leloup et al.*, 1993; *Schoenbohm et al.*, 2006], but older, likely Late Miocene (13–9 Ma) further north in Yunnan [*Clark et al.*, 2005]. In order to obtain a first order volume comparison we split the budget into three time slices of 36–24 Ma, 24–8 Ma and 8–0 Ma (Table S1), periods defined by the phases of exhumation reconstructed from the thermochronology. Figure 3 shows that in each of these time periods the volume of eroded rock is much less than that deposited offshore, implying that previously the Red River must have been drawing sediment from ranges that now lie outside the modern catchment. The mis-match between source and sink is greatest for the oldest time period, yet is still present in the 8–0 Ma period, indicating that drainage loss continued throughout the time of major plateau uplift.

[7] The nature and timing of the major capture events can be assessed through geochemical analysis of the sedimen-

[1]Auxiliary materials are available at ftp://ftp.agu.org/apend/gl/2006gl027772.

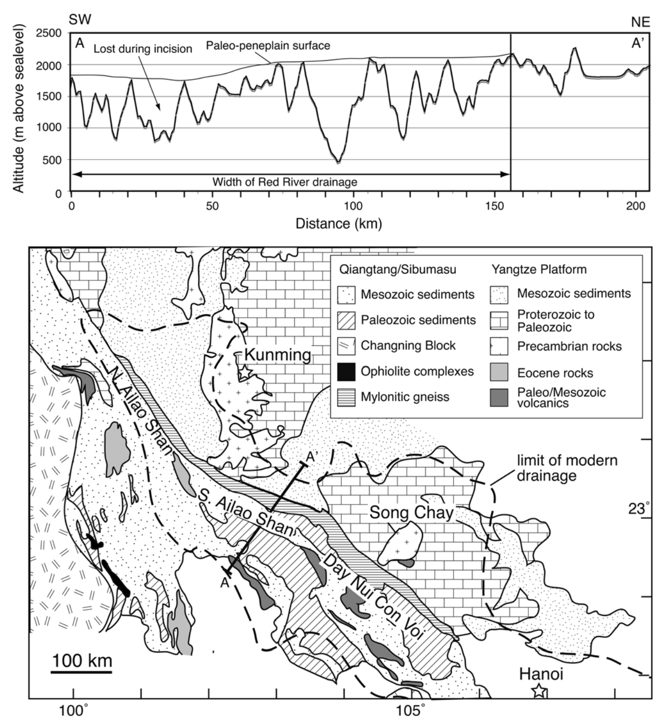

Figure 2. Geological map of the modern Red River drainage showing the metamorphic massifs that have experienced rapid exhumation during the Cenozoic. Upper section shows topography across the basin and the volume of sediment removed from the gorges during incision into the earlier peneplain.

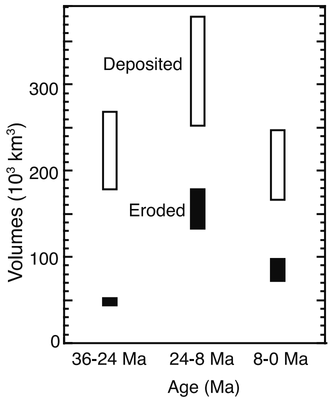

Figure 3. Volume estimates of eroded rock volumes preserved in the Hanoi, Song Hong, Beibu and southern Hainan Basins, compared to rock volumes estimated missing from the source terrains in the modern river basin. Height of bar shows uncertainty in each estimate. Data in Table S1 (see auxiliary material).

tary rocks taken from boreholes located in the Hanoi Basin of Vietnam in order to trace the evolving composition of the Red River (Figure 1a). The modern Red River follows the trace of the strike-slip Red River Fault Zone (RRFZ), which has been active since at least 34 Ma [*Gilley et al.*, 2003]. Transtensional motion across the southern end of this fault has formed the Hanoi Basin and its offshore equivalent, the Song Hong-Yinggehai Basin [e.g., *Rangin et al.*, 1995; *Clift and Sun*, 2006].

[8] The sedimentary fill of the Hanoi Basin preserves samples of Red River sediment from past times, which can be used to reconstruct changes in the composition of the clastic load in the river. These sediments have been sampled by petroleum exploration related drilling in the delta region of the modern Red River. Crucially, times of provenance change can be dated using the age control provided by the marine microfossils found within the same sedimentary rocks and analyzed by PetroVietnam. The composition of the river's clastic load must have changed when major drainage capture events removed chemically distinctive source regions from the ancestral Red River.

[9] Changes in rates of erosion caused by climatic or tectonic processes change the rate of sediment delivery to the basin, but compositional changes are a more unequivocal indicator of drainage capture in the headwaters. In this study we employed the Nd isotopic technique to assess the bulk composition of the paleo-river sediments. This method is based on the age and compositional differences between rocks in the potential source regions of eastern Tibet, southern China and northern Indochina [e.g., *Ma et al.*, 2000; *Gilder et al.*, 1996; *Li et al.*, 2000; *Lan et al.*, 2003]. These differences are transmitted to the river sediment during erosion, so that a bulk analysis of a sedimentary rock sample provides a measurement of the average Nd isotopic character of the sources that were providing material at the time of sedimentation [*Goldstein et al.*, 1984].

[10] If a source whose isotope character is different from the average is lost or gained from the drainage then this will result in a measurable change in the Nd isotope composition of the sediments carried by the river. Although the source regions are geologically complex and isotopically heterogeneous there are broad scale, coherent differences between tectonic blocks that result in isotopic differences in the erosional flux. Thus, the Cathaysia Block is isotopically more positive (higher ε_{Nd}) because of its history of Mesozoic arc magmatism [*Gilder et al.*, 1996], while the Yangtze Craton and Dabie Shan are more negative (lower ε_{Nd}) because they incorporate ancient Precambrian crust (Figure 4a) [*Ma et al.*, 2000]. ε_{Nd} values from the upper Yangtze River show a good correlation with basement values from the source regions in eastern Tibet [*Clift et al.*, 2004], indicating that the method should be effective as a provenance tool in East Asia.

[11] Nd isotopes were measured from powdered whole sediment samples (Table S2 in auxiliary material). After dissolution, Nd was concentrated using standard column extraction techniques, and isotopic compositions were determined by Finnigan "Neptune" multi-collector inductively coupled plasma mass spectrometer (MC-ICP-MS) at Woods Hole Oceanographic Institution. We calculate the parameter ε_{Nd} [*DePaolo and Wasserburg*, 1976] using $^{143}Nd/^{144}Nd$

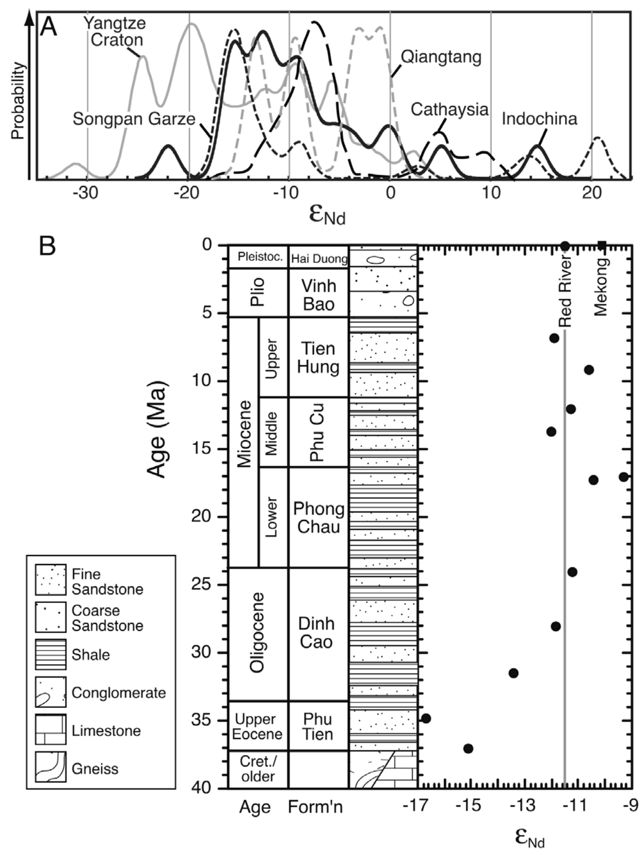

Figure 4. (a) Nd isotopic compositional ranges of possible source terrains in the paleo-Red River (data in Table S3). (b) Sedimentary log of the drilled sequence in the Hanoi Basin, showing the major stratigraphic divisions and deposition ages. The right hand column shows the range of ε_{Nd} values determined for each of these units, compared with modern river values from the Mekong and Red Rivers. Grey line shows modern composition of the Red River downstream of Hanoi.

value of 0.512638 for the Chondritic Uniform Reservoir [*Hamilton et al.*, 1983].

3. Results

[12] The results of our analysis are shown in Figure 4b and demonstrate large-scale changes in the composition of the Red River clastic load since ca. 37 Ma. The most striking changes occur during the Oligocene, after which time the sediments do not depart as strongly in their isotope ε_{Nd} values from those now found in the lower reaches of the river. However, one sample deposited at 17 Ma is somewhat less negative than the modern Red River and indicates that important differences in the sediment sources still existed at that time compared to the modern day.

[13] It is noteworthy that the major Oligocene change in ε_{Nd} values is towards less negative values with time. This indicates loss from the river of sources whose ε_{Nd} values are <-15, the value of sediment at the base of the drilled section. Strongly negative ε_{Nd} values are typically associated with ancient continental crust, such as the Yangtze Craton [*Ma et al.*, 2000], so that loss of drainage into the paleo-Red River from that terrane could cause the type of isotope change seen. Pb isotope analysis of single K-feldspar grains from Eocene sedimentary rocks in the Red River offshore support this hypothesis. The Pb data show that although many Eocene grains have compositions indistinguishable from the modern river a minority population were anomalous. These grains show a good isotopic match with rocks in the Yangtze Craton, but no other known source in East Asia [*Clift et al.*, 2004]. ε_{Nd} values in southern Tibet, the Transhimalaya and Cathaysia are more positive than the Eocene sedimentary values in the Hanoi Basin and would drive changes in ε_{Nd} value in the opposite direction if they were lost from the drainage system [*Ma et al.*, 2000; *Gilder et al.*, 1996; *Debon et al.*, 1986; *Li et al.*, 2000]. However, the fall in ε_{Nd} values at 17–13.7 Ma would be consistent with loss of drainage from a younger source such as Cathaysia.

[14] Loss or gain of drainage from Indochina would not have a major effect on the river clastic load because the range of ε_{Nd} values known from this block spans the range seen in the borehole (-15 to -5) [*Lan et al.*, 2003]. Similarly, we discount erosion of Oligocene alkaline magmatic rocks associated with the RRFZ [*Wang et al.*, 2001] as the primary cause of the isotopic shift. Study of the modern Red River suggests that rocks in the RRFZ now contribute only ca. 25% of the total clastic load, of which only a small part is magmatic rather than metamorphic rock [*Clift et al.*, 2006]. As drainage loss has removed other regions from the Red River drainage the erosional contribution from these sources would have comprised even less of the total clastic flux in the past. Nd concentrations in these volcanic rocks are comparable or slightly greater than upper continental crust [*Wang et al.*, 2001], suggesting that their influence on the bulk sediment value would be modest.

[15] The loss of drainage to the Red River from the Yangtze Craton, possibly from the Dabie Shan region, via what is now the middle Yangtze is consistent with the model of flow from the middle Yangtze from northeast to southwest into the Red River prior to the major reorganization (Figure 1b) [*Clark et al.*, 2004]. Flow would then have reversed to the modern situation at the time of capture in the Oligocene. Lesser shifts in the opposite isotopic direction could reflect loss of drainage from the upper Pearl River or even from the Tsangpo River during the Early Miocene.

4. Dating Drainage Capture and Uplift

[16] The implication of these data is that some of the most important drainage capture events in the Red River occurred before the end of the Oligocene, ca. 24 Ma, maybe as early as 28 Ma, although there is evidence for continued readjustment in the Miocene. The probable loss of drainage from the Yangtze Craton prior to 24 Ma implies a change in regional gradient since the Eocene. If the middle Yangtze River reversed direction at this time then the overall gradient of East Asia must have reversed to a dominant downslope to the east direction from its pre-collisional down to the west state. An Oligocene capture event is consistent with oxygen isotope and paleobotanical data that places southern and central Tibet close to modern elevations prior to 10–15 Ma [e.g., *Garzione et al.*, 2000; *Spicer et al.*, 2003], possibly as early as the Oligocene [*Rowley and Currie*, 2006]. The elevation in eastern Asia was not similar to the modern values at that time, yet the evolving provenance points to a far-field, tilting effect, synchronous with early mountain-building in central Tibet. Although Miocene-Recent isotopic variability is low and does not require major drainage capture by itself, the fact that the mass balance shows continued mis-match after the end of the Oligocene (Figure 3) requires continued drainage loss from the Red River since 24 Ma, and even after 8 Ma. The loss of sources with similar isotope character to the red River average would be predicted from this study and suggests that the headwaters of the Salween and Mekong, draining the Qiangtang Block may have been lost during the Miocene or later.

[17] *Clark et al.* [2005] used the (U-Th)/He low temperature thermochronology system to date the incision of the gorges in Yunnan as starting at 13–9 Ma, while *Schoenbohm et al.* [2006] favored accelerated Pliocene surface uplift in the upper Red River drainage. These ages are much younger than the capture ages implied by our study, but are not inconsistent. Drainage capture must predate gorge incision. The former reflects the initial stages of uplift, not the major surface uplift seen later. Models of plateau evolution involving lower crustal flow and progressive eastward expansion of the plateau with time [e.g., *Royden et al.*, 1997] would predict such a progression of topographic evolution.

5. Conclusions

[18] We conclude that the sediments deposited by major rivers on continental margins are effective tools for reconstructing the development of drainage systems onshore. New Nd isotopic data presented here show major change in provenance of the Red River, starting during the Oligocene and continuing into the Miocene. At the same time we show that the volume of sediment in the offshore basins is much greater than the volume of rock removed from modern river basin, requiring large-scale loss of drainage

from the Red River since the Eocene. The direction of change in Nd isotope composition, coupled with existing Pb isotope data from the Yinggehai Basin points to the Yangtze Craton as being the most likely source that was supplying sediment to the Red River in the Eocene, but which had been lost by the Miocene. This loss of drainage implies that the regional gradient of eastern Asia had reversed to the modern eastward-dipping direction by this time. Major topographic uplift in southeast Tibet-southwest China is younger, yet the process of uplift appears to have started much earlier, synchronous with mountain building in central Tibet.

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J. Blusztajn, Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA.

P. D. Clift, School of Geosciences, University of Aberdeen, Aberdeen AB24 3UE, UK. (p.clift@abdn.ac.uk)

A. D. Nguyen, Vietnam Petroleum Institute, Trung Kinh, Yen Hoa, Cau Giay, Hanoi, Vietnam.