Provenance, routing and weathering history of heavy minerals from coastal placer deposits of southern Vietnam

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Abstract

Heavy mineral rich sands along the coastal margin of southern Vietnam often contain commercial deposits of ilmenite and zircon but their origin is unknown. A multi-method approach based on petrology, geochemistry and detrital zircon geochronology was used to define the provenance and transport history of these mainly Quaternary sands. A trend of progressive enrichment of ilmenite TiO_2 content, from north to south, was observed. This reflects increased levels of weathering attributed to a wider coastal margin and shelf in the south combined with a succession of erosion and reburial events associated with interstadial and interglacial sea-level changes. Weathering took place during lowstands. Detrital zircon U-Pb age signatures collected from 25 major river outlets along the coast of Vietnam helped to locate potential sand sources. Prominent age groups spanning 90-120 Ma and 220-250 Ma with a minor group at 400-500 Ma are present in all of the detrital zircon U-Pb age distributions of contemporary beach sands and Quaternary coastal dune placer deposits. Proterozoic grains are also present but constitute < 10% of dated grains. The main source terrain for the placer sands is southern Vietnam where there are widespread outcrops of Mesozoic magmatic rocks. Detrital zircon U-Pb age signatures from river sands that drain this area are identical to zircon age distributions in placer sands. River sands from northern Vietnam, the Mekong and its delta contain abundant Paleozoic and Proterozoic zircons, which are largely absent from the placer sands, and so are ruled out as primary sources.

Keywords: Ilmenite, zircon U-Pb, provenance, Vietnam, weathering, seal-level change

1. Introduction

Beach and dune placer deposits occur along the 3260 km coastline of Vietnam, as well as offshore in water depths up to 30 m or more, are economically important sources of ilmenite, rutile and zircon (Fig. 1). The heavy mineral rich sands are mainly found in beach dunes, beach ridge, washover and backshore deposits associated with Holocene to Pleistocene sealevel changes. Onshore deposits occur as bands, typically 1-4 m thick, that extend 1-3 km inland from the coast, and are up to 10 km in length. Most of the high-value deposits are found south of latitude 16°N particularly in the central SE Vietnam provinces Ninh Thuan and Binh Thuan (Fig. 1), to the northeast of Ho Chi Minh City. Surveys made in 2011 by the Department of Geology and Mineral Resources of Vietnam estimated that there are at least 650 million tons of ore reserves along the coastal margins between northeastern Vietnam and Vung Tau in the south. Sand ilmenite content typically varies from 10 to 100 kg/m^3 although some locations have concentrations well above this. Rutile contents are usually less than 1 kg/m^3, although in some places it can reach up to 3-4 kg/m^3 (e.g., coastal areas north of Da Nang). Zircon abundances also vary; the highest average content (up to 12 kg/m^3) can be found in the coastal sections of Ham Tan in Binh Thuan Province (Fig. 1). Mineral grain sizes are typically in the range of 0.16-0.25 mm. Understanding the origin of these minerals and the processes by which they became concentrated is the primary motivation of this study.

Ilmenite is an important source of titanium oxide. Fresh unaltered ilmenite has TiO_2 wt% values up to the stoichmetric value of 52.6 wt%. Chemical weathering and alteration, especially in oxidising and/or acidic environments, can change ilmenite chemistry by reducing Fe and Mn, increasing Ti and adding Al, Si, Th, P, V and Cr (Pownceby, 2010). The distribution and proportions of the different types of altered grains in the heavy mineral sands influences their commercial value as a source of Ti, and therefore it is important to understand the distribution and proportions of the different types of altered grains in the deposits which requires identifying where the alteration occurred and defining grain transport history.

Coastal sands along the southeast-central coastline of Vietnam typically comprise an outer and inner sand barrier. The former consists of loose white sand that sometimes form tombolos (e.g., Ho Gom Peninsula). The inner sand barrier located up to 20 km inland consists of light yellow to reddish yellow sands that include dunes found at elevations over 100 m above sea level, such as in the area north of Vung Tau or Ham Thuan Bac district (Fig. 1). Whether these sands are locally derived is unclear. The aim of this study is to better understand the environmental processes that led to the alteration and concentration of the heavy minerals and to define where the sand came from. It is known that the sands are closely linked to sea-level oscillations during the Quaternary, especially Holocene glacioeustatic changes between 8 and 5 ka (Stattegger et al., 2013). Falling sea level causes remobilisation of coastal sands deposited during highstands and increases bedrock erosion inland. Larger volumes of sediment would have been more intensely weathered during glacial periods (Wan et al., 2017) and the subaerial exposure of unconsolidated shelf sediments during associated lowstands would have affected ilmenite chemistry by causing enrichment in TiO_2. Wave action and longshore drift would also have contributed to the winnowing process, sorting grains according to size and density, hence it is entirely possible that sand grains are far removed from their original source areas.

2. Regional geology and geomorphology

The source and volume of beach sands depend on wind, wave and tide regimes as well as local erosion and fluvial transport rates. Detailed study of a river catchment in northern coastal Vietnam has indicated that greatest erosion reflected by river bedload and chemistry occurs within the mountainous regions where precipitation rates are highest, and that both weathering and erosion rates are linked to monsoon intensity (Jonell et al., 2016). Transport of sediment to the coast is dominated by discharge from the Mekong River in the south and by the Song Ma and Song Hong (Red River) in the north. Between these large rivers, that have their headwaters in Tibet and southwest China, the central areas of Vietnam are more locally drained by relatively small river catchments (Fig. 2) that have their headwaters in the nearby steep mountain ranges of the central highlands. Despite their small size, these rivers have been important sources of sediment to the coast and shelf as there is a relatively short distance between the wet highlands and the coastal plain, evidenced by high Quaternary sedimentation rates (from 0.5 to 1.2 m/ka) on the local continental shelf (Schimanski and Stattegger, 2005).

The trend of the coastline and shelf areas of Central Vietnam tend to follow the NNW- and NW-striking faults formed during the Triassic or earlier. Ordovician to Permo-Triassic granulite and amphibolite facies metamorphic rocks of the elevated Kontum Massif, which broadly lies between latitudes 14°N and 15°N, form the northern margin of the study area. Whilst zircon U-Pb geochronology has recorded Proterozoic ages between 1480-1350 and 900-600 Ma for local orthogneiss (Nguyen, et al., 2001; Tran, et al., 2003), charnokites, biotite-sillimanite-cordierite-garnet gneiss, schists, amphibolites, and granitoids originally mapped as Archean and Proterozoic have since been dated as Silurian and Triassic (Indosinian) (Carter et al., 2001; Nam et al., 2001; Hiet et al., 2015, 2016). These rock types are not seen south of latitude

13°N where Mesozoic granitoids dominate. West of Nha Trang are late Carboniferous-early Permian rocks of the Dac Lin Formation. These comprise terrigenous sediments interbedded with intermediate volcanics, mainly andesitic basalts and tuffs. During the Triassic, closure of Tethys and final welding between Indochina and South China blocks caused significant deformation across much of northern Vietnam. This event is known as the Indosinian orogeny. Stratigraphy and radiometric ages of magmatic and metamorphic rocks support a Middle Triassic age for final closure of the Paleo-Tethys ocean (Faure et al., 2014). The study area was relatively unaffected by deformation related to this event. Triassic rocks are mainly confined to the northern part of the study area where the Mang Yang Formation includes rhyolites and tuffs associated with intracontinental rifts (Tran et al., 2011). Jurassic rocks are more widespread and occur as andesites, dacite and tuffaceous sandstones (Deo Bao Loc Formation). They are especially widespread in the western area between latitudes 13°30’N and 12°N. By contrast, the eastern region is dominated by Cretaceous magmatic rocks related to a former active continental margin. The widespread occurrence of arc-related magmatic rocks across the study area, including granitoids and rhyolites, is linked to subduction of the Palaeo-Pacific oceanic crust beneath southern China, Vietnam and southern Borneo (Shellnut et al., 2013; Hall and Breitfeld, 2017).

Within the study area there are three main suites of Cretaceous magmatic rocks. The Dinhquan and Deoca complexes are found along the South Vietnamese coast. Petrological characteristics of the Dinhquan complex comprise hornblende-biotite diorites, granodiorites and minor granites. The

Deoca complex consists of granodiorite, hornblende-biotite granite (phase I), biotite-hornblende granite, granosyenite and biotite syenite (phase II), and granite porphyry, granular aplite and pegmatite (dike phase). U-Pb zircon ages range from 88±1.5 – 109±7.0 Ma (Thuy et al., 2004) to 115.4±1.2 – 118.2±1.4 Ma (Shellnutt et al., 2013). The Ankroet Complex is smaller than the Dinhquan and Deoca complexes and is located further inland, at higher elevations. Rock types include medium to coarse grained porphyroid biotite granite. Published zircon U-Pb ages are 93.4±2.0 – 96.1±1.1 Ma (Thuy et al., 2004) and 86.8±1.6 Ma (Shellnutt et al., 2013). Geochemical work by Shellnut et al (2013) show the upper Lower Cretaceous granitic batholiths are I-type (partial melting of dehydrated middle/lower crust) and the Upper Cretaceous (i.e., ~90 Ma) granitic rocks have compositions similar to A-type (differentiated mafic parental magmas) associated with an extensional tectonic regime, most probably trench retreat caused by slab rollback. Ankroet rocks are associated with this extensional setting.

Cenozoic fluvial-shallow marine clastic sedimentary rocks in the study area are the Oligo-Miocene Di Linh Formation, the early Pliocene to Pleistocene Song Luy Formation, and the late Pliocene to Pleistocene Ba Mieu Formation. Study of detrital zircon U-Pb ages from these units recorded abundant Cretaceous ages, as well as Permian–Triassic and Ordovician–Silurian sources. The youngest unit also records a significant increase in Precambrian zircons (Hennig et al., 2018). Also found across the study area are widespread late Cenozoic basaltic lava flows up to several hundred metres thick (Hoang and Flower, 1998). Alkali basaltic magmatism began in the middle Miocene and has a geochemistry that fits with sources of recycled eclogitic oceanic crust from the Hainan plume (An et al., 2017). Eruptions and lava flows often appear to have exploited local fault zones re-activated by South China Sea opening.

Patterns of sediment accumulation and concentration of heavy mineral sands along the coastal shelf and margins appear to track past sealevel changes. Direct evidence to support this can be found in optically stimulated luminescence (OSL) dating studies of stratigraphically oldest barrier sands exposed at Suoi Tien (10°57’16”N - 108°15’30”E) and Hon Gom (12°41.64’N - 109°45.27’E) (Fig. 1) (Quang-Minh et al., 2010) that include layers enriched in ilmenite and zircon. These gave deposition ages ranging from 8.3±0.6 to 6.2±0.3 ka BP, contemporaneous with the local postglacial maximum sealevel highstand. Much older red shallow marine sands at Suoi Tien were dated to 101±16 ka whilst white sand at the bottom of the sequence could be as old as 276±17 ka and correspond to an earlier sea-level highstand. Detailed reconstructions of mid to late Holocene sealevel for Southeast Vietnam can be found in Stattegger et al. (2013).

Although sealevel fluctuations are important, the concentration of heavy minerals likely involved a combination of factors that included sediment transport history along the shelf and coastline (influenced by sediment supply) and hydrodynamic conditions. The latter is dominated by the East Asian monsoon system that blows from the northeast in winter and southwest in the summer. The northeast monsoon has most impact on northern Vietnam and the southwest monsoon on central and southern regions (Pham, 2003). Although seasonal reversal of the monsoon system also switches longshore currents from southerly to northerly, the long-term trend of sediment transport can also be affected by local coastal geomorphology. This makes it difficult to predict long-term trends in coastal sediment transport, as demonstrated by modeling studies of longshore transport to define impacts of sealevel changes associated with climate change (Dastgheib et al., 2016).

3. **Methods and Approach**

The study area covers the section of Vietnamese coastline where most heavy mineral sands are found, which is between 15°N and 10°N (Fig. 1). Since placer deposits represent biased sand composition we used a multi-method approach and defined the geochronological, geochemical and mineralogical signatures of representative placer deposits to locate sand source areas and define the extent of alteration and transport. Results are then compared against data collected from each of the main rivers along the Vietnamese coastline including 2 samples (X and Y) from the upper Mekong within (Laos (Fig. 2). This approach will enable a model of locally derived *vs* longshore transport derived to be tested.

Sampling of placer deposits included nearby contemporary beach sands as these might preserve geographic links to source areas compared to older sands that are likely to have seen more extensive reworking and mixing, although reworking of older sediments would negate this assumption. Recognising that during transport selective entrainment based on variations in grain density produces a compositional bias we sampled sands with a typical grain size range between 65-500 μm. River sands were collected as close to river mouths as possible from active channel beds and point bars where heavy minerals tend to be concentrated. Beach sands were sampled (Fig. 3) in areas documented as rich in heavy minerals and taken from dark sand layers in the upper shoreface following removal of the lighter coloured top few centimeters. Also included are sand samples from onshore shallow boreholes drilled in prospective mining areas. In all cases efforts were made to avoid areas subject to obvious anthropogenic disturbance. In total 25 river and 18 onshore placer sand samples (typically between 1 to 2 kg) were collected.

Quantification of mineral types and abundances was made using automated energy-dispersive X-ray spectroscopy (SEM-EDS) coupled with expert software analysis on a QEMSCAN® platform which allows micron-scale mapping and mineral identification of samples (Pirrie and Rollinson, 2011). Polished grain mounts of untreated sands were scanned at a resolution of 10 µm yielding c. 5000 to 12000 grain counts per slide. The acquired EDS spectra were interpreted automatically by reference to a database of mineral compositions.

Detrital zircon U-Pb geochronology is used to help define ilmenite provenance since both Ilmenite and zircon are normally found in similar source rock types and would be expected to behave similarly during transport as they have similar specific gravities (4.5-4.7). Detrital zircon geochronology is widely used in provenance studies due to stability of the mineral and U-Pb system (e.g., Jonnell et al., 2017; Singh et al., 2017). Detrital zircon grains were separated by standard heavy liquid techniques. Grains for dating were selected randomly from polished grain mounts and analysed by laser ablation inductively coupled plasma mass spectrometry at the London Geochronology Centre based in University College London using a New Wave 193 nm laser ablation system coupled to an Agilent 7700 quadrupole-based ICP-MS. Typical ablation parameters used 25 μm spots with a 10 Hz repetition rate and an energy fluence of ca. 2:5 J/cm^2. Instrumental mass bias and depth-dependent inter-element fractionation of Pb, Th and U were corrected for using Plesovice as an external zircon standard (Sláma et al., 2008). Time-resolved signals that record evolving isotopic ratios with depth in each crystal were processed using Glitter 4.4 data reduction software. This removed spurious signals caused by inclusions, mixing of growth zones or fractures. Calculated $^{206}Pb/^{238}U$ ages were used for grains younger than 1000 Ma, and the $^{207}Pb/^{206}Pb$ age for older grains. Grains with a complex growth history or disturbed isotopic ratios, with > +5/-15% discordance, were rejected.

To characterize ilmenite chemistry and to test for ilmenite alteration by weathering grains (circa 100 per sample) from representative river and placer sands were selected for electron microprobe analysis. A JEOL JXA-8100 Electron Probe Microanalyzer Scanning Electron Microprobe fitted with an Oxford Instruments X-act PentaFET Precision detector was used to carry out the analyses on polished grain mounts. Qemscan mineral maps helped with grain identification.

4. Results and Interpretation

4.1 Petrology

Table 1 summarises mineral abundances of representative river and Quaternary sands. Despite a wide presence of basaltic rocks olivines are rarely found in river sands and none were detected in the Qemscan analyses of untreated sand (Table 1). Pyroxenes are present in river sands but are missing from the coastal placer sands suggesting that there has been loss due to weathering. Minerals diagnostic of heavy to medium grade metamorphic rocks are common. Similar abundances of high-grade metamorphic minerals siliminite, kyanite and andalusite are present in both river and beach sands, although they are more abundant in the area between latitudes 14-16°N where outcrops of high-grade Proterozoic metamorphic rocks are more widespread. Amphiboles are especially common in the river sands between 12 and 16°N but abundances systematically decrease to the south (Fig. 4). By contrast, amphiboles are sparse in the contemporary beach sands (Table 1) suggesting either removal by weathering and physical abrasion, helped by its cleavage (Garzanti et al., 2015), or density sorting during transport. The latter is unlikely given that the ultrastable high-grade metamorphic minerals, siliminite and kyanite, which are only slightly denser than amphibole, are present in both river and beach sands (typically 0.1 to 0.4% of grains, Table 1). Aside from loss by weathering and abrasion it is also possible that the absence of amphiboles reflects minimal south-directed longshore transport, i.e., rivers sands are not dispersed very far along the coast. The latter seems more likely as the denser minerals garnet, rutile, ilmenite and zircon that do not breakdown as easily as amphibole during transport, also show decreasing abundances between northern and southern rivers and that levels in the beach sands always have a lower content than river sands. By contrast, levels of feldspars increase southwards in river samples but remain low in most heavy mineral sand samples. This provides clear evidence that some density separation is taking place in the marine environment.

4. 2. Ilmenite geochemistry

Results of a subset of samples selected for ilmenite microprobe analyses (Fig. 5) show that although some fresh unaltered ilmenite grains are present most ilmenites have been altered and this increased grain titanium contents to above stoichiometric levels (i.e., > 52.6 wt%). Plot 5A, of river sands, shows that there are some regional differences whereby the proportion of altered grains increases to the south. This implies that rivers in the north of the study area deliver fresher ilmenite to the coast and offshore. Plot 5B compares ilmenite from Holocene sands (Quang-Minh et al., 2010) along the coast. These data also show a trend of increased levels of weathering to the south. Comparison between river sands and nearby Holocene sands (Plot 5C) show dissimilar distributions supporting alteration after river deposition. Plot 5D compares modern beach sands along the coast and again the greatest amount of alteration is seen in the south.

4.3. Detrital zircon U-Pb river sand results

Data from each of the main river outlets along the coast of Vietnam provide a simple way of capturing signatures of the local geology against which coastal sand data may be compared (full analytical results are provided in the supplementary section). A summary of age distributions of individual river samples (Fig. 6), displayed as Kernel density (KDE) plots (Vermeesch, 2012), show rivers from northern and central Vietnam drain older rocks than rivers in southern Vietnam (Fig. 3). Both the Song Hong (Red River) and Mekong have age distributions dominated by a wide range of Proterozoic ages that reflect source rocks in the catchments beyond Vietnam, e.g. Mekong samples X and Y from Laos (Fig. 2). The proportion of 400-500 Ma zircons is seen to increase southwards at the expense of Proterozoic grains (Fig. 6). South of 14°N, river (sample L onwards) zircon age distributions are dominated by either Permo-Triassic, Cretaceous or Ordovician-Silurian peaks (Fig. 6). The Permo-Triassic ages are likely to be volcanic rather than granitic as the main rocks types in the study area are rhyolites and tuffs belonging to the Mang Yang Formation although Triassic granulites are known in the Kontum area (Carter et al., 2001). The majority of age spectra contained a few Proterozoic ages, some of which are clearly related to inherited cores (Supplementary Figure 1). This observation is consistent with Shellnut et al., (2013) who noted magma mixing with older basement was required to explain the composition and inherited ages of the Cretaceous granites.

As visual comparison of KDE plots is subjective the data, were also plotted as Multidimensional Scaling (MDS) maps (Vermeesch, 2013). The MDS approach, based on Kolmogorov–Smirnov effect size, group samples with similar age spectra, and pull apart samples with different spectra. The MDS map (Fig. 6) clearly shows two groups of samples. The left group comprises rivers from northern Vietnam plus the Mekong that have abundant Proterozoic ages. The right-hand group comprises river samples from central and southern Vietnam which are dominated by Permo-Triassic and Cretaceous age peaks. These two groups reflect changes in regional geology whereby northern Vietnam is dominated by Proterozoic and Paleozoic metamorphic basement, compared to the south where Mesozoic granitoids and Cenozoic basalts dominate. A transition between these groups occurs around the Kontum massif, which marks the northern limit of the main study area. The catchment of river K (Da Rang) spans this junction and therefore plots between the two main clusters. Based on these results it will be possible to identify if any of the heavy mineral sands originated from northern Vietnam.

4.4. Detrital zircon U-Pb coastal sand results

KDE plots of detrital zircon ages from coastal Quaternary (Q) and modern beach (MB) sands (Fig. 7) show prominent age groups spanning 90-120 Ma and 220-250 Ma plus a minor group at 400-500 Ma. The age distributions are remarkably similar across the whole study area, differing only in the proportions of zircons within each age group. The accompanying MDS plot suggests samples Q1 and Q2, from north of Nha Trang (Fig. 1) are different from the rest but this is simply due to fewer Cretaceous ages compared to the other samples, despite being located less than 50 km from the Cretaceous Deo Ca magmatic Complex. The Da Rang (river K) is local to samples Q1 and Q2 and shows a similar age distribution (Fig. 7) although there are fewer Cretaceous and Ordovician-Silurian zircons. South of the Da Rang, all other rivers, apart from the Mekong, are dominated by Cretaceous zircons.

5. Discussion

Heavy mineral sand mineralogy data support derivation from a mixture of magmatic and high-grade metamorphic lithologies. Many sands contain trace amounts of the high-grade metamorphic minerals sillimanite and kyanite (present in both river and coastal sands) but olivine and pyroxenes are missing despite the widespread occurrence of Neogene basalts throughout southern Vietnam (see Table 1). Likely sources of sillimanites are outcrops of biotite-sillimanite-cordierite-garnet gneiss in the Kontum district. This is supported by the higher amounts of sillimanite in rivers G and H (Fig. 2) that drain this area. However, sillimanite is also present farther south in the Song Cai (L in Fig. 2) and in Holocene heavy mineral sands near Phan Rang (Q4 in Fig. 1), a region dominated by Cretaceous granites. Rocks west of Nha Trang have been mapped as Proterozoic amphibole gneiss and schists so it is conceivable that sillimanite rocks may also exist in this area.

Feldspar contents in river sands, which are typically between 10 and 40%, have been reduced to < 2% in most heavy mineral sands indicating considerable density separation (and/or weathering) within the marine environment. Whilst none of these observations enable specific source areas to be identified, several common trends have been recognized amongst the petrological, geochemical and geochronological datasets that reflect the sediment routing system. Amphibole abundances decrease from north to south and ilmenite TiO_2 content increases southwards. Relatively fresh ilmenite is delivered to the oceans by rivers in central Vietnam (e.g., Song Cau) compared to rivers in the south (e.g., Sai Gon), where alteration due to weathering is more developed (Fig. 5A). However, ilmenite TiO_2 content in river sands do not match local heavy mineral deposits (Fig. 5C). Collectively, this evidence shows most of the alteration must have taken place after deposition by rivers. One possibility is that the wider coastal plains found in the south are more conducive to intermediate storage (and weathering) before remobilisation and final deposition (Fig. 8).

Southward widening of the SE Vietnam Shelf area has not only increased the distance between sediment sources to the middle and outer shelf but also created a wide plain that would have been exposed to weathering during the late Pleistocene and Holocene lowstands. With rising sealevel some of this sand would have been remobilised and transported inland, especially during the Holocene highstand between 6-7 ka. Sand was subsequently reworked by wave activity and redeposited during interstadial and interglacial transgressions. The narrow continental shelf farther north and the proximity of the mountainous terrain to the coast limit the amount of surface area exposed weathering in the northern and central coastal areas.

Studies of modern and late Pleistocene to Holocene stratigraphy of the shelf areas of central and southern Vietnam (Dung et al., 2013, 2014; Stattegger et al., 2013; Tan et al., 2014) have identified at least five major seismic units and three bounding surfaces that can be linked to known sealevel adjustments including relict beach-ridge deposits at water depths of about ~130 m below present that are associated with the last glacial lowstand. More importantly, in relation to understanding the processes by which sands became weathered and enriched in heavy minerals, studies (Bui et al., 2013; 2014) have noted an absence of falling stage systems tract deposits. This can be explained as the result of inner and middle shelf deposits being subjected to erosion and reworking during successive sea-level falls following highstands and reworking again during the following transgression. Repeating cycles of reworking would also have been influenced by strong monsoon driven bottom currents evidenced by numerous NE–SW oriented sand waves that today are found at modern water depths of 20-40 m (Bui et al., 2013). Figure 8 shows former coastlines associated with past lowstands and their relationship to onshore and offshore placer sands (Quang-Minh et al., 2010; Stattegger et al., 2013).

Detrital zircon data help to define where placer sands came from. Results from rivers along the coast of Vietnam show clear differences in zircon age distributions between northern Vietnam and central to southern Vietnam that directly reflect changes in the local geology (Fig. 6). Differences between river and placer zircon age distributions (Fig. 9) rule out sources from northern and central Vietnam, which are dominated by older rocks. Exceptions are Mekong river samples that yielded significant numbers of Precambrian zircon ages. Similar old ages are also found in the late Pliocene to early Pleistocene Ba Mieu Formation (proto-Mekong) found east of Ho Chi Minh City (Hennig et al., 2018). Much of this formation has been eroded away and therefore if these rocks (and paleo Mekong deposits in general) were an important source there should be significant numbers of Precambrian zircon ages present in the coastal sands. That this is not the case shows that Mekong river sands (modern or ancient) could not have been the main source of the placer sands. Geochronological and geochemical characteristic of placer and contemporary sands support a local origin defined by river catchments that are dominated by Cretaceous magmatism associated with an active continental margin, i.e., the Da Lat zone and areas to the south. Apart from Quaternary samples Q1 and Q2 that contain a larger proportion of ages between 220-250 Ma and 400-500 Ma, there is no significant difference between modern and older sand deposits (Fig. 7). This is likely due to mixing associated with changes in sealevel. Lack of Precambrian grains in the coastal placer deposits and beach sands rule out significant longshore transport from the north or reworking of paleo-Mekong sands in the south.

6. Conclusions

Placer sands along the coastal margins of central and southern Vietnam have been enriched in heavy minerals by cycles of deposition, weathering and erosion, and reburial associated with interstadial and interglacial sealevel changes. Weathering took place during lowstands. Geochemical and geochronological data show sands were derived from river catchments that contain outcrops of Cretaceous magmatic rocks. Results do not support significant longshore transport from northern Vietnam or from the Mekong delta in the south. Had there been significant transport from the north, placer sands would contain large numbers of zircons with Proterozoic and Paleozoic ages that typify the geology of these areas, including the large catchment area of the Red River that extends into South China. Mekong sources can be ruled out for similar reasons. Ilmenite sources were observed in all of the main river outlets along the southern to central Vietnamese coastline although fresh unaltered grains were mainly found in the central region. A progressive enrichment of ilmenite TiO_2 content was observed from north to south due to more intense weathering related to a widening of the shelf area. This would have increased surface area exposure of unconsolidated shelf sediments to weathering during glacial sea-level lowstands and remobilisation and mixing during subsequent transgressions.

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FIGURE CAPTIONS

Table 1. QEMSCAN mineral percentages (by volume) for untreated river and Quaternary beach sands from central and southern Vietnam.

Figure 1. Locations of placer and beach sands samples and main commercial extraction sites in southern Vietnam. Samples with illmenite composition data, and mineralogical data reported in Table 1, are also indicated.

Figure 2. Locations of river sand samples collected from each of the main river outlets along the coast of Vietnam. Sample prefixes are given in brackets.

Figure 3. Map of study area geology showing locations of sand samples

Figure 4. Abundance of amphiboles in river sands from central Vietnam as a fraction of total grains scanned on the Qemscan slide.

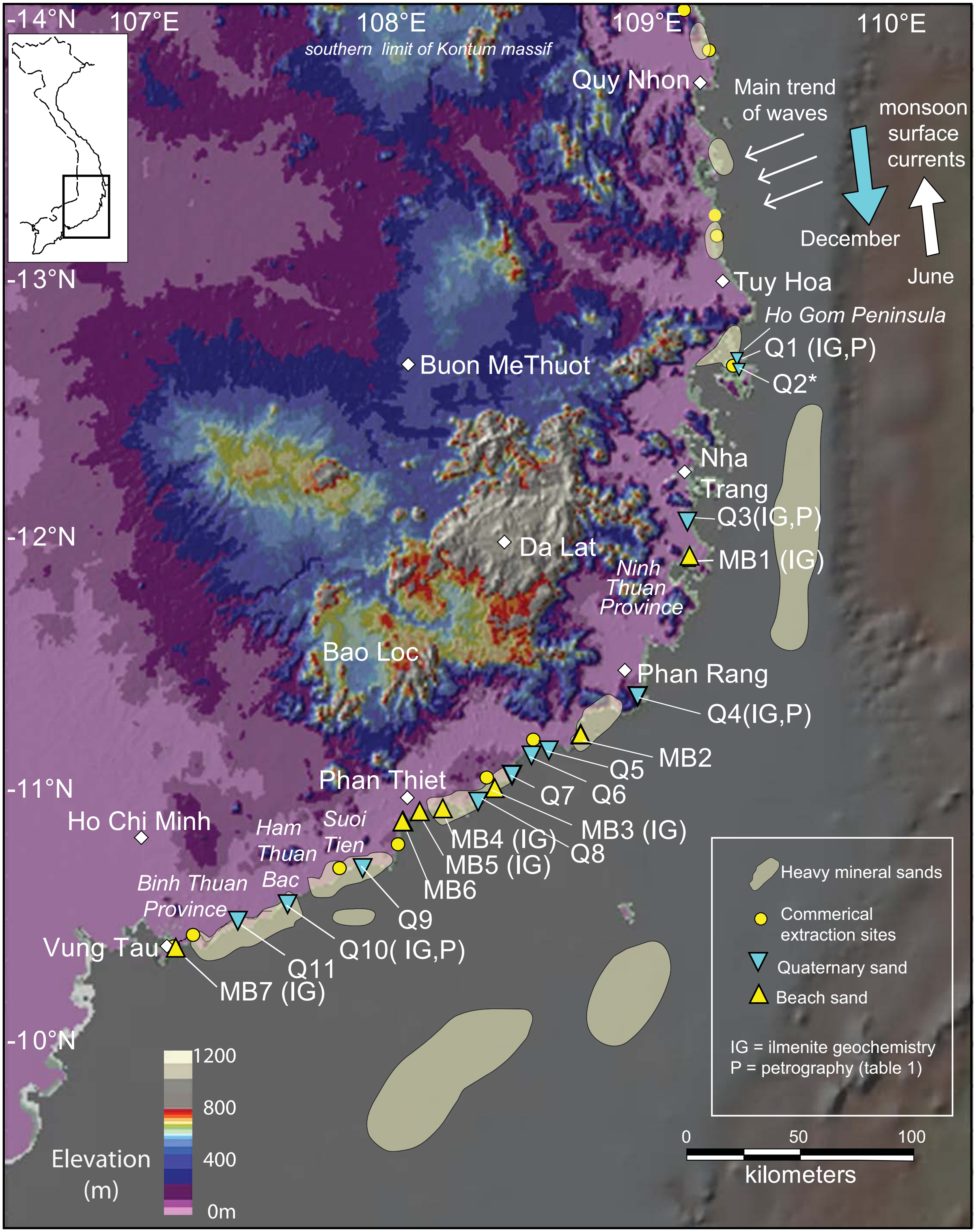
Figure 5. Ti and Fe contents of ilmenite grains from river and coastal sand samples.

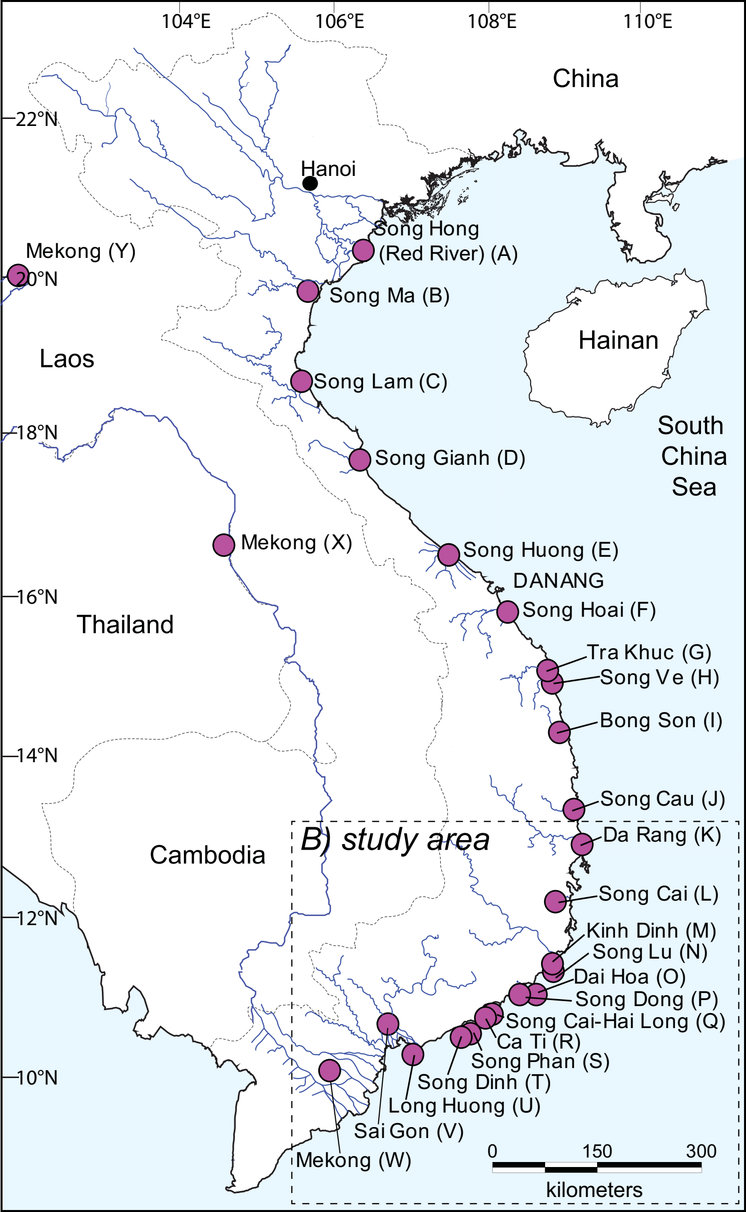
Figure 6. Kernel density and Multidimensional Scaling plots of the detrital zircon U-Pb results from the river samples shown in Figure 2.

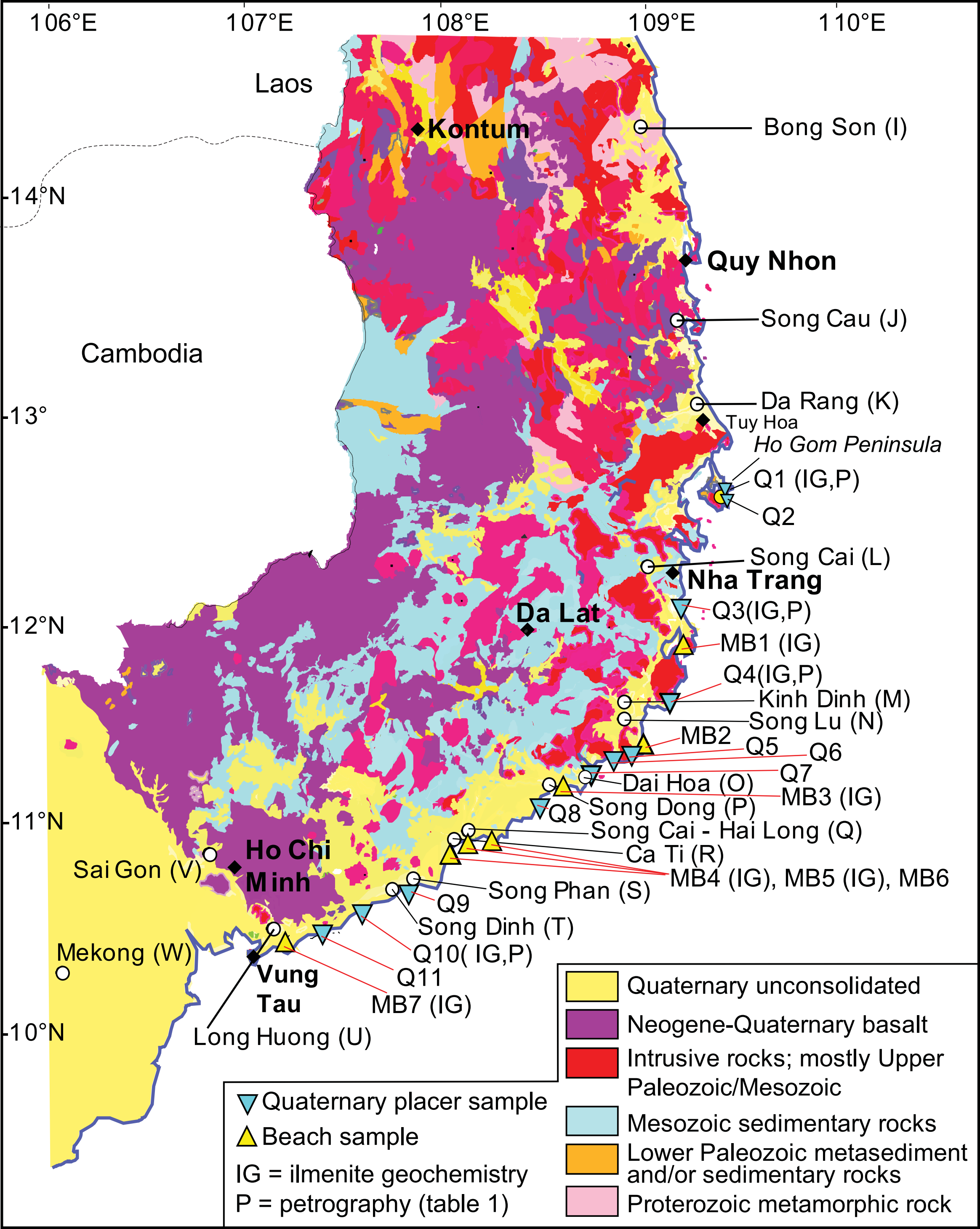
Figure 7. Kernel density and Multidimensional Scaling plots of detrital zircon U-Pb results from coastal sands. Prefix Q indicates a Quaternary sand and MB modern beach sands.

Figure 8. Relationship between late Pleistocene to Holocene sealevel change, shorelines and locations of the heavy mineral sands. The lower plot shows the link between OSL dated sands and Holocene sea level based on data from Quang-Minh et al., (2010) and Stattegger et al., (2013).

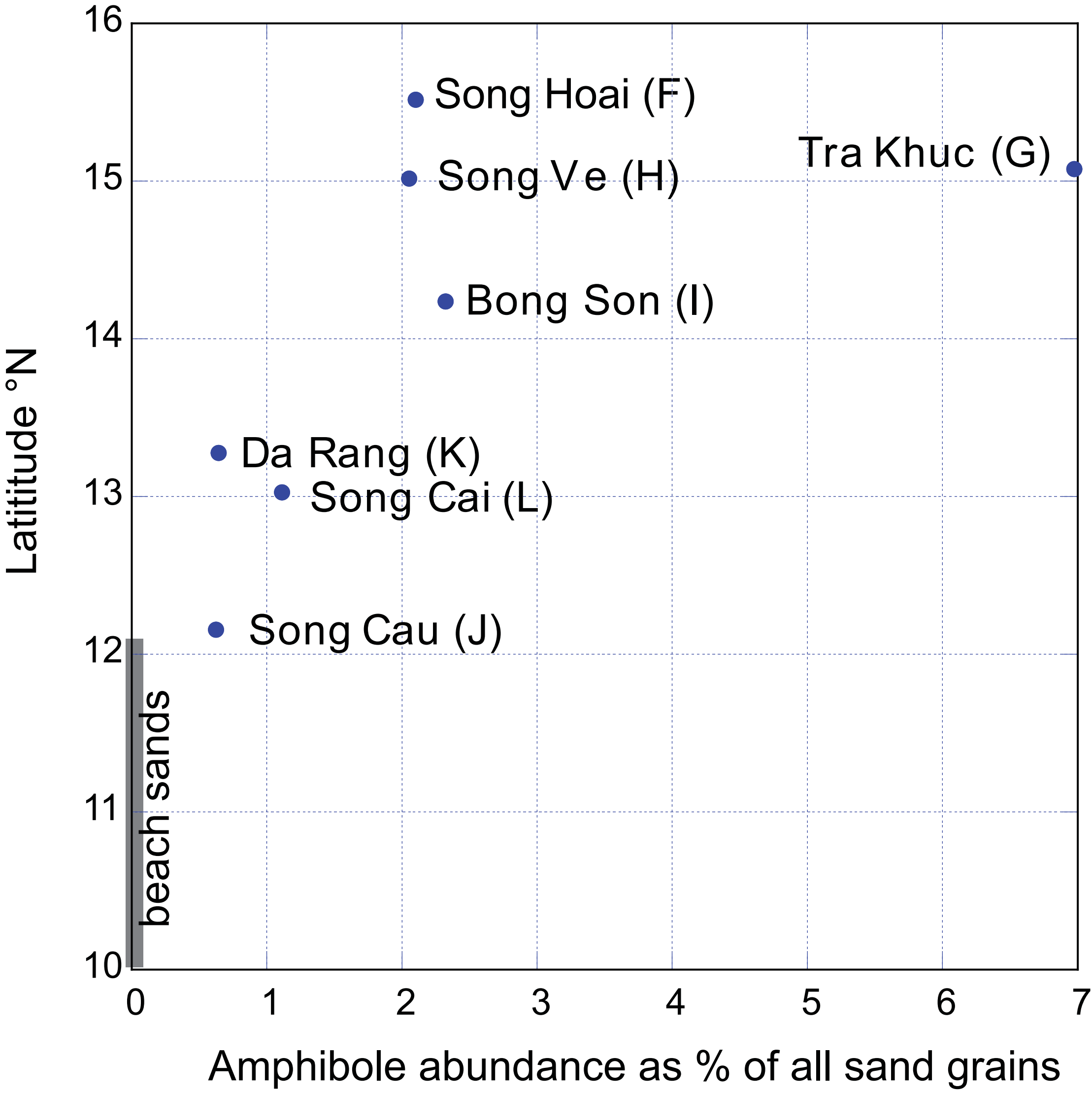
Figure 9. Multidimensional Scaling plot combining all detrital zircon samples apart from the Mekong and Red rivers that have been excluded due to their markedly different age spectra that rule out these rivers as sand sources.


-14°N
107°E
108°E
109°E
110°E
southern limit of Kontum massif
Quy Nhon
Main trend of waves
monsoon surface currents
December
June
-13°N
Tuy Hoa
Ho Gom Peninsula
Q1 (IG,P)
Q2*
Buon MeThuot
Nha Trang
Q3(IG,P)
-12°N
Da Lat
MB1 (IG)
Ninh Thuan Province
Bao Loc
Phan Rang
Q4(IG,P)
MB2
Q5
Phan Thiet
Q7
Q6
-11°N
MB3 (IG)
Ho Chi Minh
Ham Thuan Bac
Suoi Tien
MB4 (IG)
Q8
MB5 (IG)
MB6
Binh Thuan Province
Q9
Q10(IG,P)
Vung Tau
Q11
MB7 (IG)
-10°N
1200
800
400
0m
Elevation (m)
Heavy mineral sands
Commerical extraction sites
Quaternary sand
Beach sand
IG = ilmenite geochemistry
P = petrography (table 1)
0
50
100
kilometers

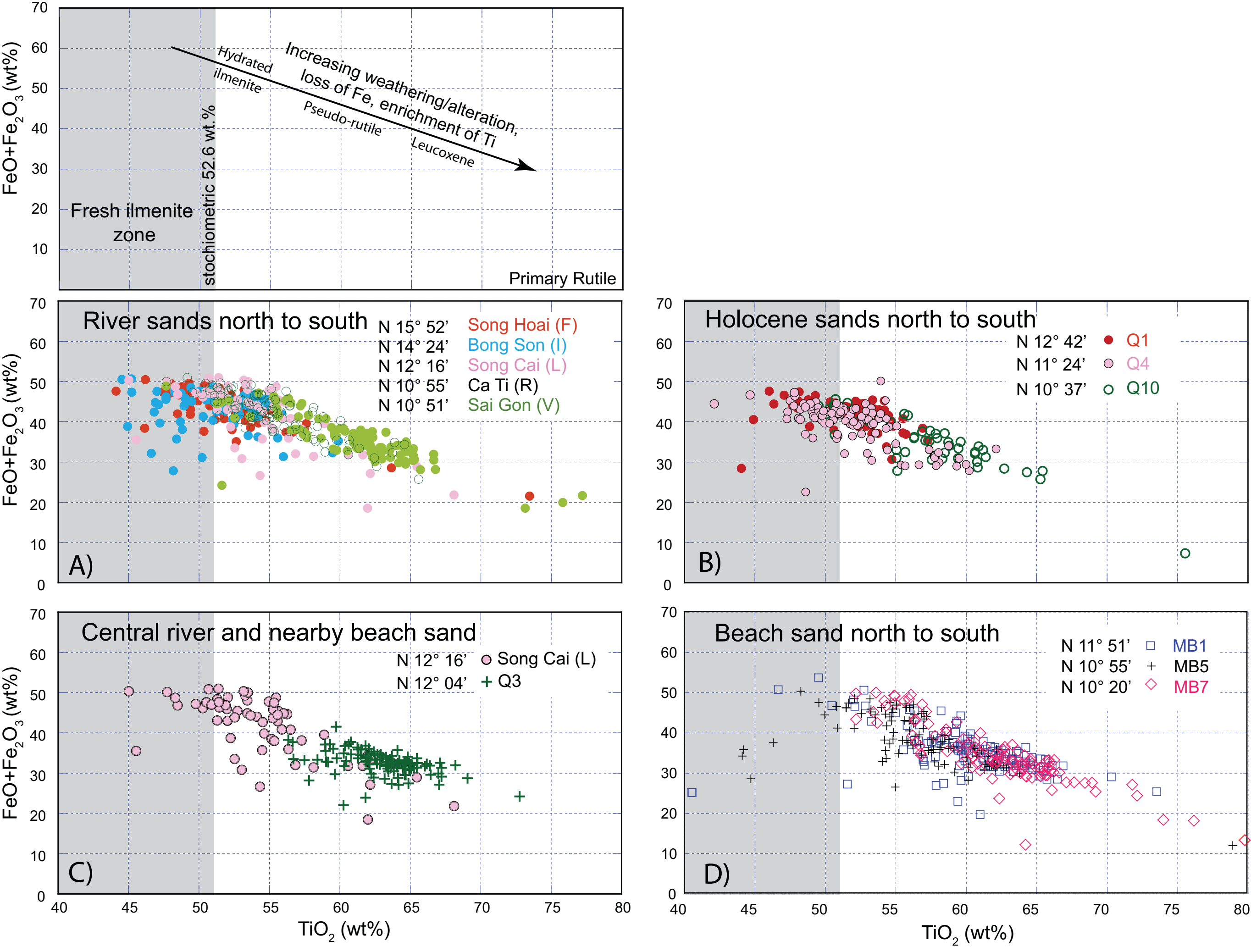

104°E
106°E
108°E
110°E
22°N
20°N
18°N
16°N
14°N
12°N
10°N
China
Hanoi
Song Hong
(Red River) (A)
Mekong (Y)
Song Ma (B)
Laos
Hainan
Song Lam (C)
South
China
Sea
Song Gianh (D)
Mekong (X)
Song Huong (E)
DANANG
Song Hoai (F)
Thailand
Tra Khuc (G)
Song Ve (H)
Bong Son (I)
Song Cau (J)
B) study area
Da Rang (K)
Cambodia
Song Cai (L)
Kinh Dinh (M)
Song Lu (N)
Dai Hoa (O)
Song Dong (P)
Song Cai-Hai Long (Q)
Ca Ti (R)
Song Phan (S)
Song Dinh (T)
Long Huong (U)
Sai Gon (V)
Mekong (W)
0
150
300
kilometers



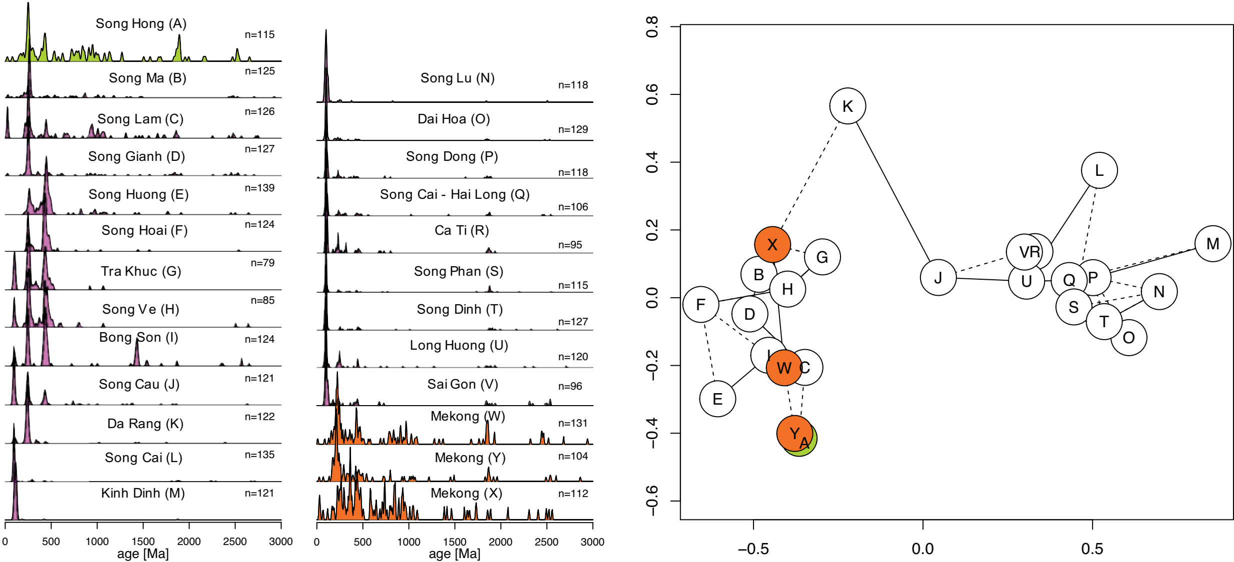
106°E
107°E
108°E
109°E
110°E
14°N
13°
12°N
11°N
10°N
Laos
Cambodia
Kontum
Quy Nhon
Tuy Hoa
Nha Trang
Da Lat
Ho Chi Minh
Vung Tau
Bong Son (I)
Song Cau (J)
Da Rang (K)
Ho Gom Peninsula
Q1 (IG,P)
Q2
Song Cai (L)
Q3(IG,P)
MB1 (IG)
Q4(IG,P)
Kinh Dinh (M)
Song Lu (N)
MB2
Q5
Q6
Q7
Dai Hoa (O)
MB3 (IG)
Q8
Song Dong (P)
Song Cai - Hai Long (Q)
Ca Ti (R)
MB4 (IG), MB5 (IG), MB6
Song Phan (S)
Q9
Song Dinh (T)
Q10(IG,P)
Q11
MB7 (IG)
Long Huong (U)
Sai Gon (V)
Mekong (W)
Quaternary unconsolidated
Neogene-Quaternary basalt
Intrusive rocks; mostly Upper Paleozoic/Mesozoic
Mesozoic sedimentary rocks
Lower Paleozoic metasediment and/or sedimentary rocks
Proterozoic metamorphic rock
Quaternary placer sample
Beach sample
IG = ilmenite geochemistry
P = petrography (table 1)



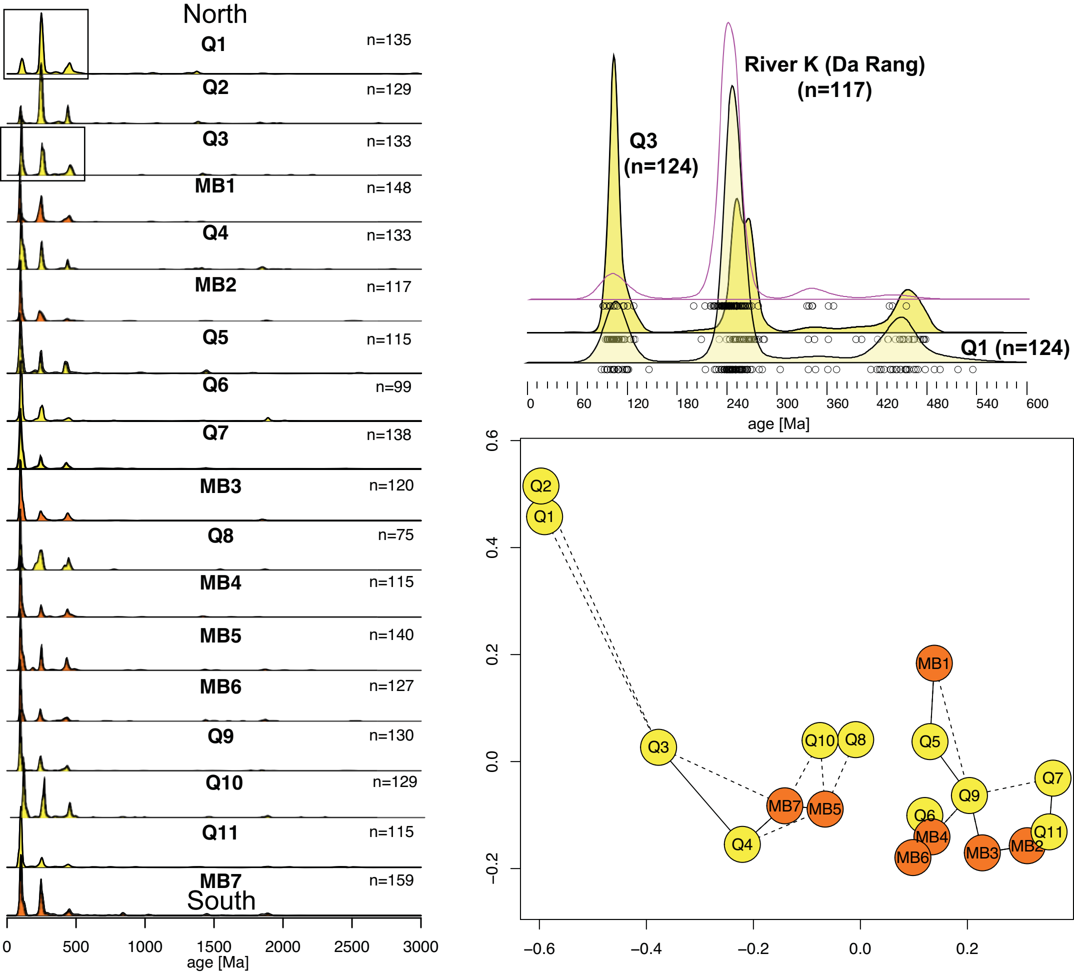
Song Hoai (F)
Tra Khuc (G)
Song Ve (H)
Bong Son (I)
Da Rang (K)
Song Cai (L)
Song Cau (J)
beach sands
Latititude °N
16
15
14
13
12
11
10
0
1
2
3
4
5
6
7
Amphibole abundance as % of all sand grains



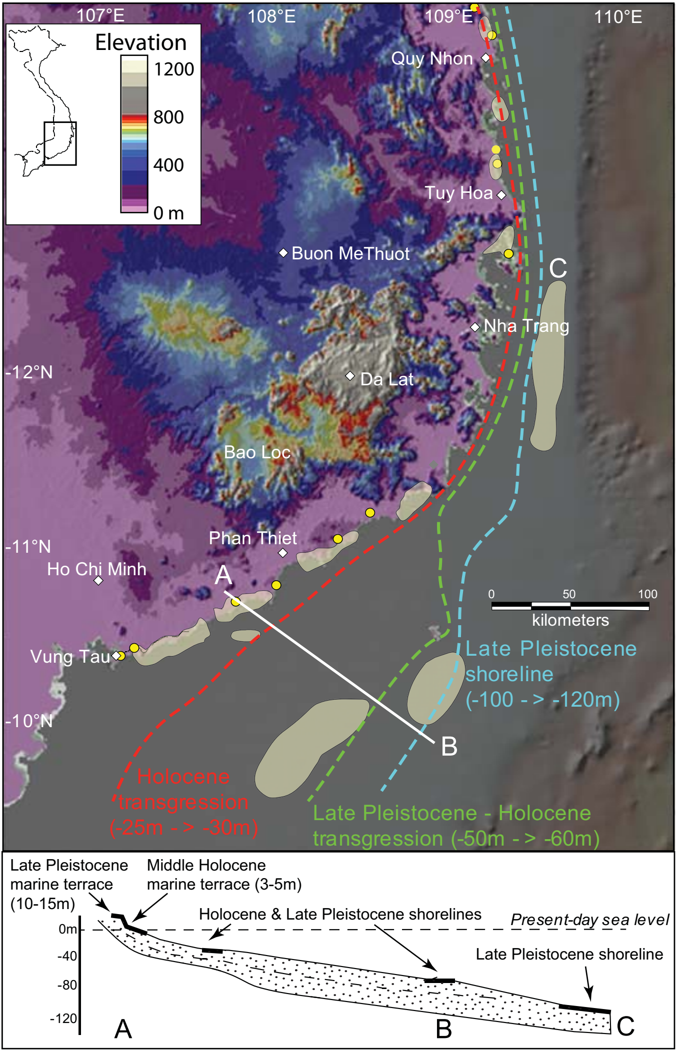
FeO+Fe2O3 (wt%)
Fresh ilmenite zone
stochiometric 52.6 wt.%
Hydrated ilmenite
Pseudo-rutile
Leucoxene
Increasing weathering/alteration, loss of Fe, enrichment of Ti
Primary Rutile
River sands north to south
N 15° 52' Song Hoai (F)
N 14° 24' Bong Son (I)
N 12° 16' Song Cai (L)
N 10° 55' Ca Ti (R)
N 10° 51' Sai Gon (V)
A)
Holocene sands north to south
N 12° 42' Q1
N 11° 24' Q4
N 10° 37' Q10
B)
Central river and nearby beach sand
N 12° 16' Song Cai (L)
N 12° 04' Q3
C)
Beach sand north to south
N 11° 51' MB1
N 10° 55' MB5
N 10° 20' MB7
D)
TiO2 (wt%)

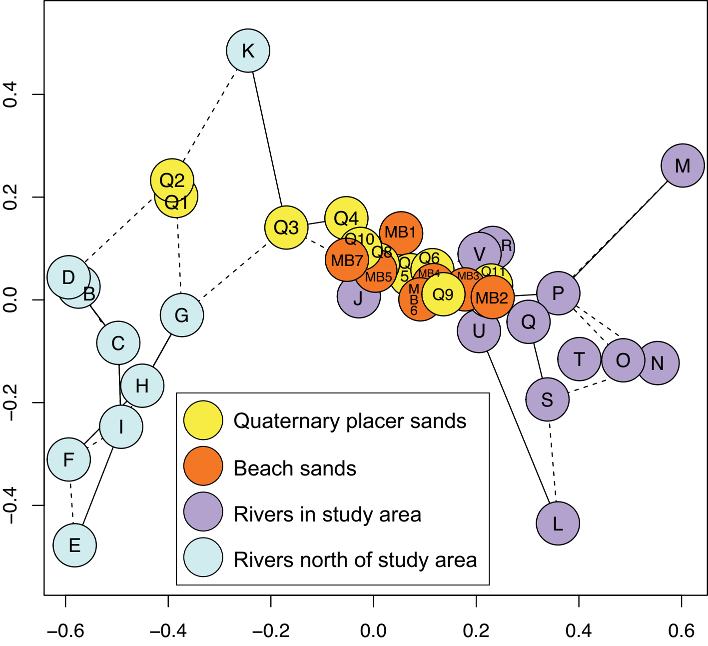


Song Hong (A) n=115
Song Ma (B) n=125
Song Lam (C) n=126
Song Gianh (D) n=127
Song Huong (E) n=139
Song Hoai (F) n=124
Tra Khuc (G) n=79
Song Ve (H) n=85
Bong Son (I) n=124
Song Cau (J) n=121
Da Rang (K) n=122
Song Cai (L) n=135
Kinh Dinh (M) n=121
Song Lu (N) n=118
Dai Hoa (O) n=129
Song Dong (P) n=118
Song Cai - Hai Long (Q) n=106
Ca Ti (R) n=95
Song Phan (S) n=115
Song Dinh (T) n=127
Long Huong (U) n=120
Sai Gon (V) n=96
Mekong (W) n=131
Mekong (Y) n=104
Mekong (X) n=112
0 500 1000 1500 2000 2500 3000
age [Ma]
0.8 0.6 0.4 0.2 0.0 −0.2 −0.4 −0.6
−0.5 0.0 0.5
K L M J VR U Q P N S T O X G B H F D I W C E Y A



North
Q1 n=135
Q2 n=129
Q3 n=133
MB1 n=148
Q4 n=133
MB2 n=117
Q5 n=115
Q6 n=99
Q7 n=138
MB3 n=120
Q8 n=75
MB4 n=115
MB5 n=140
MB6 n=127
Q9 n=130
Q10 n=129
Q11 n=115
MB7 n=159
South
0 500 1000 1500 2000 2500 3000
age [Ma]
River K (Da Rang) (n=117)
Q3 (n=124)
Q1 (n=124)
0 60 120 180 240 300 360 420 480 540 600
age [Ma]
0.6 0.4 0.2 0.0 −0.2
−0.6 −0.4 −0.2 0.0 0.2
Q2 Q1 Q3 Q4 MB7 MB5 Q10 Q8 MB1 Q5 Q9 Q7 Q6 MB4 MB6 MB3 MB2 Q11


107°E
108°E
109°E
110°E
Elevation
1200
800
400
0 m
Quy Nhon
Tuy Hoa
Buon MeThuot
C
Nha Trang
-12°N
Da Lat
Bao Loc
Phan Thiet
-11°N
Ho Chi Minh
A
0
50
100
kilometers
Vung Tau
Late Pleistocene
shoreline
(-100 - > -120m)
-10°N
B
Holocene
transgression
(-25m - > -30m)
Late Pleistocene - Holocene
transgression (-50m - > -60m)
Late Pleistocene
marine terrace
(10-15m)
Middle Holocene
marine terrace (3-5m)
Holocene & Late Pleistocene shorelines
Present-day sea level
0m
-40
-80
-120
Late Pleistocene shoreline
A
B
C


0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
K
Q2
Q1
Q3
Q4
MB1
Q10
MB7
Q8
MB5
Q5
Q6
MB4
MB3
Q11
MB6
Q9
MB2
V
R
M
P
J
U
Q
T
O
N
S
L
D
B
C
G
H
I
F
E
Quaternary placer sands
Beach sands
Rivers in study area
Rivers north of study area