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Editorial Overview

Introduction to the special issue "Analysis of sediment properties and provenance: Tools for palaeo-environmental reconstruction"

The ability to trace sediments from their sources to sedimentary basins is a prerequisite for quantitative analysis of Earth-surface dynamics. Traditionally, sedimentary geologists have been concerned with the inverse problem of deducing the characteristics of sediment-source areas from their products, a field conceived as sedimentary provenance analysis. The recent revival of sedimentary provenance analysis has greatly benefitted from the continuously expanding range of tools to quantify sediment properties (isotopic, age, mineral, chemical and petrographic composition, grain-size, -shape, and -density distributions, etc.) and interpret such data in palaeo-geographic, -tectonic and -climatic terms. As a result, quantitative sedimentary petrography has become a mainstay of sedimentary basin analysis.

The breakdown of basin fills into source-specific sediment budgets is arguably the most important task of provenance analysis, because it offers the attractive prospect of quantifying rates of weathering and denudation in the geological past. The development of quantitative provenance techniques is ultimately driven by the desire to reconstruct ancient sediment-routing systems, which provides the key to understanding rates of mass transfer at the Earth's surface, even in cases where source areas have been consumed by the machinery of global tectonics and the basin fill is all that remains, a situation not uncommon in "deep time" studies.

The working group on sediment generation (WGSG) resulted from an ad-hoc meeting at restaurant "Les Arenes" during the IAS conference in Alghero (Italy) in 2009, and has established itself as an informal assemblage of scientists working on topics such as sediment generation and dispersal, composition and provenance, as well as mass balancing of sediment-routing systems and modelling of relevant processes. The major scientific aim of the WGSG is to increase our understanding of sediment generation in the broadest sense of the word by developing an integrated quantitative methodology for sediment analysis which may be applied at different spatial and temporal scales. Its second aim is to promote education of graduate students through dedicated short courses, and exchange of specialized knowledge on aspects of quantitative sediment analysis, modelling and interpretation of results. Three such courses are currently on offer: an annual course on sedimentary provenance analysis organised by the University of Göttingen, a biennial course on heavy-mineral analysis organised by the University of Milano-Bicocca, and a course on sandstone diagenesis organised by the University of Erlangen-Nürnberg.

The first two WGSG workshops, held in Arcavacata di Rende, Italy (2010) and Göttingen, Germany (2014), respectively, resulted in special issues of the journal "Sedimentary Geology" (published in 2012 and 2016, respectively). The scientific results of the third WGSG meeting in Leuven, Belgium (2016), are summarized in this volume. This special issue title reflects the aim of the third meeting, which was to bring together scientists working on methodological aspects of sedimentary provenance analysis and scientists who are applying such techniques for palaeo-environmental reconstruction of Quaternary systems. In keeping with this aim, the contributions to the 3rd WGSG meeting in this special issue have been grouped into three categories.

Methodological contributions

The first category focuses on the development of research methods to quantify sediment properties for palaeogeographic, palaeoenvironmental and palaeoclimate reconstructions.

One of the best-established tools for sediment provenance analysis is U-Pb detrital zircon geochronology, which is most often measured by LA-ICP-MS. However, analytical strategies and protocols vary widely within the community, which has led *Zimmermann et al.* to evaluate the importance of target-spot selection. Based on two large U-Pb zircon data sets, they demonstrate that both zircon cores and rims should be analyzed to detect all age peaks and optimize characterization of the source rock. In addition, they recommend using U-Pb Concordia ages, which result in smaller age uncertainties than single isotope ratios throughout geological time, and removes the need to separately assess discordance.

Another well-established tool for discrimination and interpretation of sediment provenance is garnet chemistry. *Tolosana-Delgado et al.* introduce a new multivariate discrimination scheme for assignment of chemical garnet composition to metamorphic facies. Their approach is based on a large database, and a hierarchical discrimination approach involving three steps. The five major host-rock groups are eclogite-, amphibolite- and granulite-facies metamorphic rocks as well as ultramafic and igneous rocks. Prior probabilities are assigned to each sample based on the geological setting. The discrimination scheme has been tested for a large variety of crystalline rocks covering all of the five major groups and several subgroups from various geologic settings. In most cases, garnets are assigned correctly to the respective group. Exceptions typically reflect the peculiarities of the regional geologic situation.

Fourier transform infrared (FTIR) spectra contain information on the mineralogical composition of sediments, because each mineral has a unique absorption pattern in the mid-IR range. However, conversion of FTIR spectra to mineral concentrations is not straightforward. *Hahn et al.* used a calibration set of ca. 200 sediment samples whose mineral

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compositions were determined by X-ray diffraction in order to develop multivariate, partial least-squares regression models relating mineral contents to FTIR spectra. Their results indicate that the most common minerals (e.g. quartz, K-feldspar, illite, plagioclase, smectite, and calcite) can be reasonably well predicted from FTIR spectra, but more work needs to be done to firmly establish FTIR as a quantitative method.

Shang et al. applied dynamic image analysis (DIA) to characterize the grain size and shape of Chinese aeolian sediments, and examine the possibility of using joint size-shape information for fingerprinting of transportation processes. Their results indicate that DIA can be a powerful tool for identifying grain-size and -shape sorting trends in multivariate records of sediment properties, as exemplified by the analysis of the silt-sized aeolian fraction of the Chinese Loess Plateau. DIA is capable of providing quantitative constraints on sediment budgets and the joint size-shape distribution of several grain populations in the data. Their study suggests that elongated and/or flat particles (with a low aspect ratio) were transported further downwind than more symmetrically shaped particles (with a high aspect ratio). Given appropriate numerical models, such data may be used to reconstruct the dominant mode of transport of ancient sediments and their transport pathways, and constrain palaeo-wind speeds.

End-member modelling algorithms extract valuable information from compositional data. They are based on the assumption that the data structure reflects mixing and permit an assessment of the number of distinct subpopulations which gave rise to the observed patterns. Depending on the material analyzed, these subpopulations may represent sediment sources, or specific combinations of selective transport processes. In recent years, a range of non-parametric algorithms developed specifically for unmixing of grain-size distributions has become available, which have been used to reconstruct past sediment fluxes in relation to climate variability. *Van Hateren et al.* carried out a comparative study to evaluate the performance of currently available algorithms using a range of data sets. Their study indicates that successful use of end-member modelling requires that the geological context is taken into account, because the "geologically feasible" number of end members determined by the algorithms is based on goodness-of-fit criteria and does not necessarily correspond to the true number of end members in the data.

Sediment-generation studies aim to elucidate the processes by which rock fragments are created from a (crystalline) parent rock. The petrographic composition of sand grains derived from granitoids, the most common igneous rocks at the Earth's surface, is mostly controlled by the relative strength and abundance of crystal interfaces. In their paper, *Weltje et al.* propose an innovative method to characterize the frequency of mineral interfaces in granitoids. Their analysis demonstrates that interface-frequencies are non-random, with isomineralic interfaces being consistently less abundant than non-isomineralic interfaces. Most importantly, they provide guidelines on how to quantify the joint variability of igneous rock texture (spatial arrangement of crystals and crystal-size distributions) and modal composition, in view of their application to sediment-generation studies.

Quaternary systems as natural laboratories

The second category of papers deals with the application of tools to analyse sediment properties and provenance in modern and Quaternary sedimentary environments. Such systems may be regarded as natural laboratories, because the conditions under which these comparatively recent deposits have formed can quite often be well constrained. Hence, many studies conducted in these natural laboratories go far beyond mere case histories and are of methodological significance as well.

Garzanti et al. used a combination of petrographic, heavy-mineral, geochemical, and zircon-geochronology datasets along source-to-sink transects covering 17^0 of latitude between southern Congo and northern Namibia to investigate how well sand composition reflects weathering under different climate conditions. As predicted by most weathering models, the authors observed increasing quartz/feldspar and decreasing plagioclase/K-feldspar ratios with increasing precipitation. Careful analysis of the sediment sources revealed that the apparent provenance signature may be artificially enhanced by tectonic uplift and recycling, which, in Angola, vary along the same latitudinal gradient as precipitation. The authors therefore conclude that sand compositional data should be interpreted with caution since they are affected by many independent processes such as provenance, recycling and hydraulic sorting, in addition to weathering.

Stutenbecker et al. applied a similarly integrated petrographic, mineralogical and geochemical approach to river sediments from the upper Rhône basin to assess the influence of anthropogenic activities and global climate change on sediment supply. Their results showed that despite having high denudation rates, the southern watersheds contribute very little to the total sediment budget, which may be explained by human activities such as sediment mining and sediment retention in large hydropower reservoirs. In addition, the authors showed that the contribution of glaciogenic sediments is currently increasing owing to the rapid retreat of Alpine glaciers during the last decades. Overall, this contribution convincingly demonstrates that anthropogenic activities significantly affect sedimentary systems at both local and regional scales.

In another region affected by rapid glacier retreat, *Piret et al.* reconstructed the origin of a megaturbidite recently discovered in one of the largest fjords of Chilean Patagonia, using a combination of geophysical and sedimentological techniques. Based on diagnostic criteria such as grain size and magnetic profiles, foraminifera abundance, bulk organic geochemical signatures and radiocarbon ages, they were able to demonstrate that the 7m-thick turbidite was not related to the abrupt release of 370 km^3 of freshwater from a large proglacial lake as originally thought, but was rather triggered by a large mid-Holocene crustal earthquake. Although earthquakes are frequent in Chile, this is the first description of an earthquake-triggered turbidite south of the Chile Triple Junction.

It is generally accepted that river sands of the Upper Rhine area derive almost exclusively from the northern Alps. In their contribution, *Hülscher et al.* revisit this Alpine provenance hypothesis using single-grain geochemical measurements on garnet and amphibole. Their results provide evidence that provenance results are strongly grain-size dependent. Although their data confirm the predominance of Alpine garnets in the fine-sand fraction of the sediment, analysis of the medium-sand fraction revealed an Upper Rhine Graben origin. Likewise, amphibole geochemistry confirmed that a significant fraction of Quaternary sands in the Upper Rhine area originate from the graben shoulders. Their results highlight the potential of single grain geochemistry over classic optical methods of mineral identification in provenance studies, and underscore the importance of grain-size effects on the results of provenance studies.

Shifts in sediment provenance on the other side of the Alps were examined by *Amorosi and Sammartino* to unravel the stratigraphic architecture of late Quaternary alluvial, deltaic, coastal and shallow-marine strata of the Po Basin. Using chemostratigraphic analysis across three orders of bounding surfaces placed within a hierarchy of sediment packages (representing 10^5 to 10^3 years), the authors were able to successfully invoke allogenic control, in the form of tectonic, climatic, and glacio-eustatic variations, to explain the geochemical variability among the two highest-ranking units (10^5 to 10^4 years). Identifiable provenance variations on the smallest scale (10^3 years) developed in response to simple autogenic processes, such as channel avulsion and delta lobe switching. Integrating chemostratigraphy with sequence-stratigraphic studies or with high-resolution reconstructions of 3D depositional architecture is needed to correctly interpret provenance shifts recorded in sediment cores or outcrops.

Deep-time studies

The third and last category contains contributions that apply a variety of provenance tools to pre-Quaternary systems. Such systems can