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Sedimentary Geology 171 (2004) 1–11

Sedimentary Geology

www.elsevier.com/locate/sedgeo

Quantitative provenance analysis of sediments: review and outlook

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Received 15 April 2004; received in revised form 7 May 2004; accepted 12 May 2004

Abstract

Provenance analysis of sediments is aimed at reconstructing the parent-rock assemblages of sediments and the climatic-physiographic conditions under which sediments formed. Inferring sediment provenance from the final product, a basin fill, is anything but straightforward because the detrital spectrum evolves as the sediment is transported along the pathway from source to basin. Successful provenance analysis requires that the nature and extent of compositional and textural modifications to the detrital spectrum be recognised, if not quantified. The history of quantification in sediment-provenance studies is summarised and illustrated by tracking two fundamental ideas: the concept of the sediment-petrological province or petrofacies, and the relation between sandstone composition and (plate) tectonic environment. Progress in sedimentary provenance analysis has been closely linked with advancements in measurement technology. A brief survey of modern data-acquisition tools illustrates the possibilities and limitations of modern provenance research. An operational definition of Quantitative Provenance Analysis (QPA) is presented in which the central role of mass balance is acknowledged. Extension of this definition to include quantitative predictions obtained by forward modelling (computer simulation) of sediment production, as well as methodological improvements in data acquisition and processing is needed to cover likely future developments in QPA. The contributions to the special issue "Quantitative Provenance Analysis of Sediments" illustrate the intrinsic multidisciplinarity and rapid expansion of QPA.

Keywords: Provenance analysis; Sediments; Earth; Mass balance

1. Introduction

The term provenance is derived from the Latin verb provenire, meaning to come forth or to originate. In its broadest scope, provenance analysis includes all inquiry that would aid in reconstructing the litho-

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0037-0738/$ - see front matter
doi:10.1016/j.sedgeo.2004.05.007

spheric history of the Earth (Basu, 2003). In sedimentary petrology, the term provenance has been used to encompass all factors related to the production of sediment, with specific reference to the composition of the parent rocks as well as the physiography and climate of the source area from which sediment is derived. The intent of sedimentary provenance studies is to reconstruct and to interpret the history of sediment from the initial erosion of parent rocks to the final burial of their detritus, i.e., to unravel the line of descent or lineage of the sediment under investigation. The ultimate goal of provenance studies is to deduce the characteristics of source areas from measurements of compositional and textural properties of sediments, supplemented by information from other lines of evidence (Pettijohn et al., 1987).

Sedimentary provenance studies started in the 19th century with the microscopic investigation of accessory ("heavy") minerals of recent sands. According to the exhaustive bibliography of Boswell (1933), mineralogical investigation of sands prior to 1870 was entirely descriptive. The first attempts to trace accessory minerals of recent beach and river sands to their parent rocks were made by Ludwig (1874), Meunier (1877) and Michel Lévy (1878). Thürach (1884) carried out the first provenance studies of accessory minerals in ancient sediments. Retgers (1895) was the first to make explicit suggestions as to the use of characteristic minerals for determining ancient drainage directions and other palaeogeographic features. The objective of early provenance studies was to determine the parent rocks of single minerals or mineral varieties, based on detailed inventories of the accessory mineral assemblages of igneous and metamorphic rocks. The studies of Brammall (1928) and Groves (1931) exemplify the use of accessory minerals for the reconstruction of sediment dispersal from well-known parent rocks. A theoretical framework for these investigations was formulated by Brammall (in Milner, 1922), who proposed the concept of the "distributive province", defined as "the environment embracing all rocks, igneous, metamorphic and sedimentary, contributing to the formation of contemporaneously accumulated sediment" (Milner, 1962, p. 373). This qualitative concept relied on dichotomisation of the mineral assemblage (i.e., presence–absence charts), which was considered satisfactory for the purpose of stratigraphic correlation.

Quantitative investigation of accessory mineral assemblages began with the work of Fleet (1926), who introduced the method of counting grains to improve the estimation of relative mineral frequencies. Edelman (1931) strongly advocated a quantitative approach to provenance studies by analysis of the entire accessory-mineral assemblage, rejecting the qualitative criteria on which the concept of the distributive province was based. His principal objection against this concept was that the proportional contribution of a distributive province to a sediment body could have been negligible, in view of the fact that its recognition may depend on the presence of an extremely rare diagnostic mineral. Instead, he proposed the concept of the "sediment-petrological province", defined as "a sediment body that constitutes a natural unit in terms of origin, age and geographical distribution" (Edelman, 1931; Edelman and Doeglas, 1933). It gained wide acceptance as a basic element of classification in provenance studies of accessory-mineral assemblages (Hubert, 1971; Suttner, 1974; Morton, 1985). There was comparatively little interest in the major framework components of sands during the first decades of the 20th century, when accessory-mineral studies flourished. It was widely believed that "the lighter constituents do not provide a sufficient variety of minerals to yield any criteria of stratigraphical importance; quartz and feldspars are ubiquitous and that is about all that can be said" (Solomon, 1932).

Petrographic analysis of major framework constituents would not have been possible without the invention of thin-section petrography by H.C. Sorby (1880), who also carried out the first detailed investigation of quartz varieties. Judd (1886) first recognized the influence of climate on the preservation of feldspars. These early studies were expanded by Mackie (1899a,b), who established criteria for the recognition of quartz derived from igneous and metamorphic rocks and the use of feldspars as indicators of contemporaneous climate. Studies by Cayeux (1906, 1929), Goldman (1915), Gilligan (1919) and Dake (1921) illustrate that descriptive thin-section sandstone petrography was already well established at the beginning of the 20th century. Quantitative characterisation of bulk sediment properties by chemical analysis (Cayeux, 1916) was also actively developed. The first systematic quantitative investigations of sand bulk mineralogy started in the 1930s with Trowbridge and Shepard (1932), Van Baren (1934) and Russell (1937). These early studies of modal composition combined various methods of separation with mounting-and-counting techniques borrowed from accessory-mineral analysis. Krumbein and Pettijohn (1938) discussed these methods in detail in their monograph, which represents the first comprehensive overview of quantitative methods in sedimentary petrography. In the 1940s, P.D. Krynine and F.J. Pettijohn proposed the first versions of the sandstone classification schemes that are still being used (Klein, 1963; Okada, 1971). Krynine also strongly advocated the importance of tectonic control on the compositional and textural properties of sandstones, inspired by the ideas of his teacher M.S. Shvetsov, who realised already in the 1920s that sandstone mineralogy was related to tectonic setting (Folk and Ferm, 1966). The development of concepts in sedimentary petrography (lithogenesis) in Russia and the USSR was summarised by Strakhov (1971).

The introduction of a practical point-counting device by Chayes (1949) opened the way to routine measurement of modal composition from thin sections, which had a major impact on the popularity of quantitative sandstone petrography (Griffiths, 1967; Galehouse, 1971). Interest in the bulk mineralogical and textural properties of sand-sized sediments increased strongly during the subsequent decades. In the 1950s and 1960s, J.C. Griffiths made several major contributions to quantitative sedimentary petrography. He managed to condense this entire field of study into a single equation, through a conceptually coherent and rigorous approach outlined in his monograph (Griffiths, 1967). R.L. Folk (1980), a student of both Krynine and Griffiths, continued their traditions with great success, as witnessed by his influential lecture notes on sedimentary petrology from 1959, which were updated and reprinted many times. In the 1960s, framework mineralogy was used to infer parent-rock assemblages and weathering conditions in the source areas of ancient sediments. However, many of these inferences were based on scanty evidence and had been obtained without thorough investigation of modern analogues (Blatt, 1967; Suttner, 1974). The next step forward was the development of a standard data-acquisition methodology for analysis of sands, which opened the way to powerful generalisations that could only be built on extensive intercomparison of sample suites.

Provenance studies received new impulses through the work of Dickinson (1970), who established clear-cut operational definitions for grain types to improve the reproducibility of detrital modes. Subsequently, Dickinson and Suczek (1979) and Dickinson and Valloni (1980) demonstrated that modal composition of sands is largely controlled by plate tectonics, confirming earlier suggestions of Crook (1974) and Schwab (1975). The appeal of this seemingly straightforward method to infer ancient plate-tectonic settings led to an enormous interest in the study of sandstone framework mineralogy and the rapid buildup of a petrographic database (Breyer, 1983; Valloni, 1985; Dickinson, 1985, 1988). The emergence of sedimentary provenance analysis as a distinct field of study was spurred by the publication of several monographs that originated at dedicated meetings, starting with the book *Provenance of Arenites* edited by G.G. Zuffa in 1985. Subsequent milestones included *Developments in Sedimentary Provenance Studies* edited by A.C. Morton, S.P. Todd and P.D.W. Haughton in 1991 and *Processes Controlling the Composition of Clastic Sediments* edited by M.J. Johnsson and A. Basu in 1993. The monograph *Quantitative Provenance Studies in Italy* edited by A. Basu and R. Valloni in 2003 represents a collection of papers with a distinct emphasis on quantitative aspects of sediment provenance.

Some of the basic ideas about sediment provenance made their appearance already in the 19th century, to be gradually developed by later generations of researchers. For instance, the “Dickinsonian” concept of plate-tectonic control on sand composition is not very different from the Shvetsov–Krynine theory, which may ultimately be traced back to the work of Cayeux and Sorby. Another example of particular relevance to quantification of sediment provenance is the reappearance of the sediment-petrological province defined on the basis of accessory-mineral assemblages (Edelman, 1931; Edelman and Doeglas, 1933) in the form of the “petrofacies” concept commonly applied to the principal framework composition of sands (Dickinson and Rich, 1972; Ingersoll, 1983). The significance of the sediment-petrological province/petrofacies as a building block of provenance studies is highlighted by the following statement: "In its broadest aspect, the problem of provenance can be considered as a problem of accounting—making an inventory of the different types of grains contributed by different source rocks. To this, one should add the problem of the same kinds of grains coming from different source rocks" (Pettijohn et al., 1987, p. 265). An inventory of petrofacies, coupled with an understanding of their spatio-temporal distribution (volumetrics) and genesis, would be an excellent starting point for a mass-balance exercise designed to quantify the provenance of a basin fill. The study by Rittenhouse (1944), in which accessory-mineral assemblages in the Rio Grande and its tributaries were used to estimate the contributions of lower order drainage basins to sands deposited in the Middle Rio Grande Valley, provides one of the first worked examples of such a mass-balance study.

As a direct result of the recent proliferation of quantitative data-acquisition techniques, coupled with progress in data processing and modelling approaches, a new field of study aimed at solving the fundamental problem of reconstructing mass transfer from source areas to sedimentary basins has begun to emerge. One of the benchmarks in this field is the monographic quantitative study of provenance and mass balance at the active plate margin of Calabria, southern Italy (Ibbeken and Schleyer, 1991). The authors adequately captured the challenge posed by quantification of sediment provenance in their introductory statement: "If we gather adequate data about a mountainous area being eroded, we should be able to predict certain features of the resulting river-mouth sediments [. . .] Nobody expects these predictions to be verified by nature, but the interpretation of the differences between the predicted and the real sediment should improve our understanding of provenance" (Ibbeken and Schleyer, 1991, p. 2).

2. Problems of quantifying sediment provenance

The main difficulty of sedimentary provenance analysis stems from the fact that sediments are not a one-to-one image of their source, implying that parameters other than parent lithology determine their final composition (e.g., Suttner, 1974; Johnsson 1993; Cox and Lowe, 1995). Broadly speaking, clastic sediments are made up of two types of material. Detrital grains, the dominant component of coarse clastic sediments, are the residues of weathered (crystalline or detrital) parent rocks, whereas fine-grained sediments may be essentially composed of clay minerals formed by weathering of unstable minerals. Climate and topography in the source area are the main controlling factors of processes like weathering and erosion, which determine the detrital spectrum supplied to first-order tributaries at the beginning of the dispersal system connecting source and basin. Vegetation, which plays an important role as principal modulator of the output from the source area into first-order tributaries (Weltje et al., 1998), is also largely controlled by climate and topography. Weathering causes the depletion of unstable minerals like feldspars and mafic minerals (e.g., pyroxene, amphibole, biotite), whereas comparatively stable minerals like quartz and zircon, as well as clay minerals, are enriched in the detrital spectrum.

Compositional and textural characteristics of the initial detritus are modified by abrasion and sorting during transport, when sediments are carried away from their source area. While sediment is in transit, chemical alteration acts as important sediment modifier during temporary storage of the sediment in alluvial systems (Johnsson and Meade, 1990), thereby further obscuring the original detrital spectrum. In principle, the total amount of time available for transport in relation to the total amount of energy defines the relative contribution of mechanical and chemical alteration of particles (Fig. 1). Mixing of detritus from multiple sources may further modify the initial sediment characteristics, especially when dispersal pathways are complex and involve recycling of previously deposited sediments. At the site of deposition, an environmental signature (e.g., bioclasts, glauconite) may be added to the sediment causing, for the first time, a compositional change that is essentially unrelated to the initial detrital spectrum. When dealing with ancient (lithified) sediments, the role of diagenetic changes after deposition and burial should also be taken into account. During diagenesis, detrital mineral phases are subject to further alteration, the so-called intra-

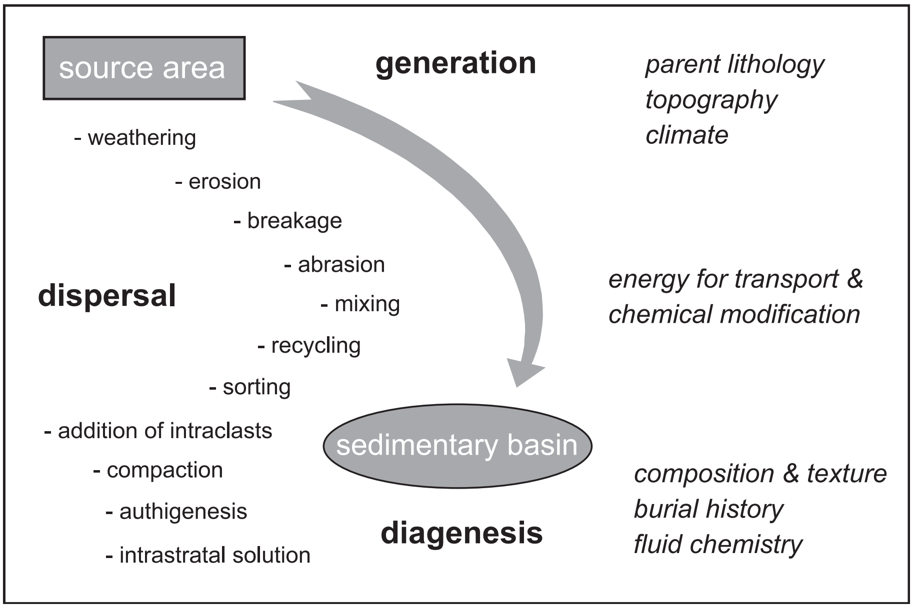

Fig. 1. Main steps in sediment evolution (bold) and principal processes that modify the composition of clastic sediments along the pathway from source area to sedimentary basin. Controlling factors (italic) are shown on the right.

stratal solution, whilst authigenic phases may precipitate. These postdepositional processes are largely controlled by the composition and texture of the sediment (grain-size distribution, grain shapes and packing density control permeability), but also by the amount and rates of subsidence (burial history), as well as by the chemistry of migrating fluids within the basin (Giles, 1997).

The ultimate properties of sediment thus reflect the parent lithology and the entire history of its modifications by weathering, recycling, transport, mixing, deposition and diagenesis. The complex web of relations between source and sediment may never be completely unravelled, because a substantial amount of information is invariably lost by the wide range of compositional and textural modifications that affect the detrital spectrum along the pathway from source to basin. The complexity of these interdependent modifications imposes certain limits on our capability to infer the characteristics of source areas from the properties of their products, just like "...we cannot tell all we want to know of a sand grain's origin from its composition alone, any more than we can deduce political history from human physiology" (Siever, 1988).

3. Data-acquisition methodologies

Chemical alteration and mechanical breakdown of source rocks, followed by sorting of particles during transport and deposition, lead to preferential enrichment of specific materials in certain grain-size fractions, and hence, sediment composition tends to be a function of grain size. For example, SiO_2/Al_2O_3 ratios typically decrease with decreasing grain size or decreasing textural maturity within a given size range because of the relative enrichment of Al-rich phyllosilicates at the expense of Si-rich phases in fine-grained materials. Suitable analytical approaches to sediment provenance therefore also depend on grain size. Successful methods to analyse, e.g., sand-sized sediments may fail when applied to finer grained materials. Cobbles and boulders potentially allow application of the full range of analytical methods that are used to study the primary source rocks, because the original mineral paragenesis is preserved and can be used to estimate metamorphic pressure–temperature(–time) paths (e.g., Cuthbert 1991). Finer grained sediments have often lost all paragenetic information due to decomposition into individual mineral grains, as well as chemical and/or mineralogical transformations.

Data acquisition in sedimentary petrology and provenance analysis follows three principal approaches: (1) the analysis of bulk composition (both petrographic-mineralogical and chemical), (2) the selective analysis of a specific group of minerals (subcompositions, most frequently used are the heavy minerals) and (3) the morphological, chemical and radiometric analysis of single grains from suitable mineral phases (single-grain techniques, also called varietal studies). Extraction of provenance-related information from sediment grain-size distributions has been discussed in considerable detail by Weltje and Prins (2003) and will not be treated here.

Chemical analysis of sediment whole-rock composition is generally based on sample crushing, powdering and disintegration or melting, followed by measurement of major, trace, and rare-earth elements using a range of techniques (AAS, XRF, NAA, ICP-MS, etc.). Whole-rock geochemistry has both advantages and disadvantages relative to detrital modes obtained by point counting. The rapid acquisition of a large number of variables with high precision and the applicability to both coarse- and fine-grained sediments are distinct advantages. The main disadvantages of whole-rock chemical analysis relative to modal analysis is its inability to separate detrital from authigenic elements and its inability to subdivide chemically similar grains according to textural criteria. Weltje (2002) reviewed point-counting techniques in sedimentary petrology and quantification of the uncertainty in detrital modes.

Sand-sized sediments allow the application of high-resolution single-grain methods for chemical and geochronological analysis, such as electron microprobe, laser-ablation ICP-MS, U/Pb SHRIMP dating and $^{40}Ar/^{39}Ar$ laser-probe dating. In silts and clays, individual mineral grains are difficult to measure even with these high-resolution techniques, and hence, analytical approaches to provenance analysis of these sediments are usually restricted to whole-rock methods supplying data on bulk mineralogy, bulk chemistry and bulk isotopic ratios (e.g., Garver et al. 1996; Bock et al. 2000). In spite of these methodological restrictions, fine-grained sediments play an important role in provenance studies because of (1) the predominance of pelitic rocks in sedimentary basins, (2) the efficiency of mixing during suspension transport that causes mud-derived provenance signals to be much more representative than sand-based provenance signals and (3) a usually much lower permeability of muds relative to sands, which reduces the extent of diagenetic modification (Blatt 1985).

Weathering, transport and postdepositional processes may considerably affect the results of traditional methods that aim at a description of grain assemblages. In contrast, most of the single-grain techniques give direct information on the parent rock. Single-grain techniques can be subdivided into three groups:

(1) Microscopic–morphological (including SEM and CL) techniques use variations in shape, colour and internal structures like zoning and fractures or streaks within a certain mineral phase to constrain different parentages (e.g., Lihou and Mange-Rajetzky, 1996; Seyedolali et al. 1997; Dunkl et al., 2001).
(2) Single-grain geochemical techniques (electron microprobe and/or laser-ablation ICP-MS analysis) allow one to determine the chemical composition and its variability among grains of a certain mineral phase for the purpose of provenance discrimination, lithologic fingerprinting and thermobarometric evidence (e.g., Morton, 1991; von Eynatten and Gaupp, 1999; Zack et al., 2002).
(3) Radiometric dating of single detrital minerals for the purpose of geochronological fingerprinting and thermochronology (e.g., Sircombe, 1999; Rahl et al., 2003; von Eynatten and Wijbrans, 2003).

All single-grain analytical techniques in provenance analysis focus on variability within a specific mineral phase (e.g., the chemical composition of detrital tourmaline). The advantage of such studies is that differences between mineral assemblages introduced by factors other than provenance (e.g., chemical stability, size, shape, density) are minimised. Single-grain techniques are potentially capable of elucidating the spatial distribution and proportions of different source rocks contributing to a drainage system or rates of exhumation and erosion in source area. However, the full potential of single-grain techniques will be realised only if their results can be firmly connected to the bulk mass transfer from source to basin, i.e., the parent-rock mass corresponding to a single grain must be known.

4. Quantitative provenance analysis: a working definition

In view of the many conceptual and practical problems of provenance analysis, it is not surprising that the development of robust, reliable and widely applicable provenance indicators has been slow and difficult. The following sample of parameters, which have been proposed as useful descriptors of sediment provenance and indicators of specific compositional modifications, serves to illustrate the state of the art of provenance studies:

- Specific morphological features of garnet or staurolite are considered to reflect intrastratal solution (e.g., Füchtbauer, 1964);
- The apatite–tourmaline index (ATi) based on heavy-mineral analysis may be used to constrain chemical alteration during temporary storage in intense weathering environments (Morton and Johnsson, 1993);
- The occurrence of specific early-diagenetic minerals like calcite and Fe oxides is suggested to mirror short-term climatic variations better than sandstone whole-rock composition (Velbel and Saad, 1991);
- High zircon+tourmaline+rutile concentrations (ZTR-index, Hubert, 1962) or Zr/Sc whole-rock ratios (McLennan et al., 1993) are considered to indicate sediment recycling;
- Continent-scale average sand(stone) composition may be used to infer the plate-tectonic setting of sedimentary basins (Dickinson and Suczek, 1979; Dickinson, 1985, 1988);
- Sand(stone) composition may be used to constrain climatic–physiographic conditions in source areas (Basu, 1985a; Weltje et al., 1998);
- Quartz-grain subpopulations of sand(stones) are indicative of parent-rock assemblages (Basu et al., 1975; Basu, 1985b), especially if supported by data on the SEM and CL properties of the quartz grains (Seyedolali et al., 1997);
- The sand generation index (SGI; Palomares and Arribas, 1993) is a measure of the capacity of one bedrock type to generate sand relative to another in a compound source area.

Many of these parameters are either qualitative or semiquantitative, i.e., they are solely capable of describing relative changes in the intensity of a certain process with respect to a single case study, but do not allow quantitative estimation of the intensity of the process in absolute terms. Other parameters may be considered absolute, but suffer from limited resolution. If rules governing the production and dispersal of sediments from known parent rocks could be fully quantified, the amount and the compositional–textural properties of sediments produced under given tectonic and climatic scenarios could be predicted. However, the current state of affairs in sedimentary provenance studies does not yet allow for such predictions. Quantitative provenance models, which relate vertical and/or lateral compositional trends within basin fills to the tectonic evolution of a source terrain, to (base-level induced) changes in sediment dispersal patterns, or to palaeoclimate fluctuations, are still in their infancy. Development and application of such models is the domain of quantitative provenance analysis (QPA).

Basu (2003) proposed a working definition of QPA, which in slightly modified form reads as follows: QPA is the quantitative assessment of the type, amount and rate of supply of detrital material from identifiable parent-rock assemblages to a basin fill. This definition places a strong emphasis on mass balance as a fundamental concept in QPA, following Molinaroli and Basu (1993). In our view, the scope of QPA includes all kind of research aiming at a quantitative characterisation of the factors controlling the compositional and textural modifications that transform a parent rock to a final deposit (Fig. 1). Hence, QPA covers the development and application of (1) analytical, statistical and numerical methods to characterise sediment properties, a subject that is intimately connected to data acquisition; (2) forward modelling, embracing all quantitative predictions of sediment supply to basins based on computer simulation of sediment-forming processes; and (3) inverse modelling, more specifically, the quantification of the volumes of individual parent rocks contributing to a basin fill, as well as the corresponding rates of erosion and tectonic processes in the source area on the basis of observed sediment properties. We wish to stress that QPA is not merely a field of application of existing quantitative methods to basin analysis. The important methodological research area of data acquisition, processing and modelling forms an integral part of QPA, because fundamental problems in this field can only be solved through the development of tailor-made methods. For instance, most provenance information comes packaged as compositional (so-called closed-sum) data, which have successfully resisted many attempts at analysis with standard statistical methods (Chayes, 1960; Aitchison, 1986; Weltje, 2002; von Eynatten et al., 2002). Obviously, there is considerable scope for research into fundamental as well as applied aspects of QPA.

5. Contents of this special issue

The contributions to this special issue reflect the full width of the rapidly expanding field of QPA. The papers have been subdivided into two groups. Papers in the first group deal mainly with methodological aspects of QPA, whereas the second group of papers focuses primarily on application of existing techniques.

The first two papers introduce new tools for analysing sediment provenance.

- Hounslow and Morton illustrate the use of magnetic mineral inclusions in clastic grains;
- Zack et al. discuss the potential of rutile geochemistry for quantitative provenance analysis.

The next three papers are devoted to statistical modelling of data in QPA.

- Weltje proposes probabilistic measures of compositional homogeneity for use with point-count data and illustrates their relevance to petrographic data-acquisition strategies;
- von Eynatten presents a statistical tool to model process-related trends in sediment composition;
- Sircombe and Hazelton tackle the problem of comparing zircon age distributions in a statistically rigorous way.

The second group of papers sets out with three contributions to a fundamental problem in QPA: the effects of selective transport on bulk mineralogy and chemistry.

- Garcia et al. focus on the extraction of provenance information from sandstones based on patterns of geochemical variability caused by entrainment sorting;
- Whitmore et al. illustrate the effects of weathering and size sorting on the composition of fluvial sediments from Papua New Guinea;
- Ohta aims to decipher provenance characteristics of the Mesozoic Nagato Basin fill by contrasting the chemistry of sand- and mudstones from the same sedimentary units.

The final section provides a sample of the diverse applications of QPA.

- Carrapa et al. illustrate the use of single-grain techniques for reconstructing early stages of Alpine collision from detritus;
- Kuhlmann et al. seek to constrain the source areas of a large Neogene delta system in the North Sea basin by Sm/Nd fingerprinting in conjunction with clay mineralogy;
- Vezzoli et al. present a mass-balance study of a fluvial drainage basin in the western Alps. The first part is devoted to estimation of the mixing coefficients of known end-member sediment types in the fluvial system. In a companion paper, Vezzoli uses the results of the quantitative provenance interpretation to estimate sediment yields;
- Le Pera and Arribas add to the growing reference database of point-count data on modern sands and discuss the principal controls on Tajo river sand provenance.

Unravelling the history of sediments is a complex and challenging task that requires interdisciplinary efforts of sedimentologists, petrographers, mineralogists, geochemists, geochronologists, structural geologists, stratigraphers, mathematical geologists and geomorphologists. Recent progress in understanding of the factors governing sediment production and supply to basins has been driven by improved data acquisition and processing methodologies, not to mention an increased effort in development and use of mathematically rigorous methods of statistical analysis and numerical modelling of sediment composition. Our intention is to capture some of the exciting new insights obtained from development and application of such methods. This special issue is intended to contribute to a deeper understanding of the potential and limitations of the broad range of analytical and statistical approaches available to students of sediment provenance. Hopefully, it will be perceived as a small but significant step towards a comprehensive quantitative model of clastic sediment production and dispersal.

Acknowledgements

This volume grew out of the session “Towards Quantitative Provenance Analysis” convened by HvE and GJW in 2003 at the joint EGS-AGU-EGU meeting in Nice, France. We thank the authors, who worked very hard to deliver the manuscripts on time. Special thanks to referees Alessandro Amorosi, José Arribas, Heinrich Bahlburg, Barbara Bock, Poppe de Boer, Sam Boggs, Rónadh Cox, Salvatore Critelli, Daniela Fontana, Kerry Gallagher, Daniel Garcia, Eduardo Garzanti, Gary Girty, William Heins, Raymond Ingersoll, H. Ishiga, Mark Johnsson, Suzanne Kairo, Joachim Kuhlemann, Maria Mange, Tom McCann, Emanuela Molinaroli, Andrew Morton, Irina Overeem, Maarten Prins, Gerd Rantitsch, Fritz Schlunegger, Sarah Sherlock, Richard Smosna, Cornelia Spiegel, Balázs Székely and Alex Woronow, who generously gave of their time and provided many valuable suggestions to improve the quality of the manuscripts. Last but not least, we thank SG editor-in-chief Keith Crook and the staff at Elsevier Science Publishers (Tirza van Daalen, Tonny Smit and Femke Wallien) for their support.

References

Aitchison, J., 1986. The Statistical Analysis of Compositional Data. Chapman and Hall, London. 416 pp.

Basu, A., 1985a. Influence of climate and relief on compositions of sands released at source areas. In: Zuffa, G.G. (Ed.), Provenance of Arenites. Reidel Publ., Dordrecht, pp. 1–18.

Basu, A., 1985b. Reading provenance from detrital quartz. In: Zuffa, G.G. (Ed.), Provenance of Arenites. Reidel Publ., Dordrecht, pp. 231–247.

Basu, A., 2003. A perspective on quantitative provenance analysis. In: Valloni, R., Basu, A. (Eds.), Quantitative Provenance Studies in Italy, Memorie Descrittive della Carta Geologica dell'Italia, vol. 61, pp. 11–22.

Basu, A., Young, S.W., Suttner, L.J., James, W.C., Mack, G.H., 1975. Re-evaluation of the use of undulatory extinction and polycrystallinity in detrital quartz for provenance interpretation. J. Sediment. Petrol. 45, 873–882.

Blatt, H., 1967. Provenance determinations and recycling of sediments. J. Sediment. Petrol. 37, 1031–1044.

Blatt, H., 1985. Provenance studies and mudrocks. J. Sediment. Petrol. 55, 69–75.

Bock, B., Bahlburg, H., Wörner, G., Zimmermann, U., 2000. Tracing crustal evolution in the southern Central Andes from Late Precambrian to Permian using Nd and Pb isotopes. J. Geol. 108, 518–535.

Boswell, P.G.H., 1933. On the Mineralogy of Sedimentary Rocks. Murby and Co., London. 393 pp.

Brammall, A., 1928. Dartmoor detritals: a study in provenance. Proc. Geol. Assoc. 39, 27–48.

Breyer, J.A., 1983. Sandstone petrology: a survey for the exploration and production geologist. Mt. Geol. 20, 15–40.

Cayeux, L., 1906. Structure et origine des grès du Tertiaire parisien: études des gîtes minéraux de la France. Imprim. Nationale, Paris. 131 pp.

Cayeux, L., 1916. Introduction à l'étude pétrographique des roches sédimentaires. Imprim. Nationale, Paris. 524 pp.

Cayeux, L., 1929. Les roches sédimentaire de France: roches siliceuses. Imprim. Nationale, Paris. 774 pp.

Chayes, F., 1949. A simple point counter for thin-section analysis. Am. Mineral. 34, 1–11.

Chayes, F., 1960. On correlation between variables of constant sum. J. Geophys. Res. 65, 4185–4193.

Cox, R., Lowe, D.R., 1995. A conceptual review of regional-scale controls on the composition of clastic sediments and the co-evolution of continental blocks and their sedimentary cover. J. Sediment. Res. A65, 1–12.

Crook, K.A.W., 1974. Lithogenesis and geotectonics: the significance of compositional variation in flysch arenites (graywackes). In: Dott Jr., R.H., Shaver, R.H. (Eds.), Modern and Ancient Geosynclinal Sedimentation, SEPM Spec. Publ., vol. 19, pp. 304–310.

Cuthbert, S.J., 1991. Evolution of the Devonian Hornelen basin, west Norway: new constraints from petrological studies of metamorphic clasts. In: Morton, A.C., Todd, S.P., Haughton, P.D.W. (Eds.), Developments in Sedimentary Provenance Studies, Geol. Soc. Lond. Spec. Publ., vol. 57, pp. 343–360.

Dake, C.L., 1921. The problem of the St. Peter sandstone. Bull.-Mo. Sch. Mines Metall. 6, 1–228.

Dickinson, W.R., 1970. Interpreting detrital modes of graywacke and arkose. J. Sediment. Petrol. 40, 695–707.

Dickinson, W.R., 1985. Interpreting provenance relations from detrital modes of sandstones. In: Zuffa, G.G. (Ed.), Provenance of Arenites. Reidel Publ., Dordrecht, pp. 333–361.

Dickinson, W.R., 1988. Provenance and sediment dispersal in relation to paleotectonics and paleogeography of sedimentary basins. In: Kleinspehn, K.L., Paola, C. (Eds.), New Perspectives in Basin Analysis. Springer-Verlag, New York, pp. 3–25.

Dickinson, W.R., Rich, E.I., 1972. Petrologic intervals and petrofacies in the Great Valley sequence, Sacramento Valley, California. Geol. Soc. Amer. Bull. 83, 3007–3024.

Dickinson, W.R., Suczek, C., 1979. Plate tectonics and sandstone compositions. AAPG Bull. 63, 2164–2182.

Dickinson, W.R., Valloni, R., 1980. Plate settings and provenance of sands in modern ocean basins. Geology 8, 82–86.

Dunkl, I., Di Gulio, A., Kuhlemann, J., 2001. Combination of single-grain fission-track geochronology and morphological analysis of detrital zircon crystals in provenance studies—sources of the Macigno formation (Apennines, Italy). J. Sediment. Res. 71, 516–525.

Edelman, C.H., 1931. Over bloedverwantschap van sedimenten in verband met het zware mineralen onderzoek. Geol. Mijnb. 10, 122–124.

Edelman, C.H., Doeglas, D.J., 1933. Bijdrage tot de petrologie van het Nederlandsche Tertiair. Verhandelingen van het Geologisch-Mijnbouwkundig Genootschap voor Nederland en Koloniën, Geologische Serie, vol. 10, pp. 1–38.

Fleet, W.F., 1926. Petrological notes on the Old Red Sandstone of the West Midlands. Geol. Mag. 63, 505–516.

Folk, R.L., 1980. Petrology of Sedimentary Rocks. Hemphill Publ. Co., Austin. 182 pp.

Folk, R.L., Ferm, J.C., 1966. A portrait of Paul D. Krynine. J. Sediment. Petrol. 36, 851–863.

Füchtbauer, H., 1964. Sedimentpetrographische Untersuchungen in der älteren Molasse nördlich der Alpen. Eclogae Geol. Helv. 57, 157–298.

Galehouse, J.S., 1971. Point counting. In: Carver, R.E. (Ed.), Procedures in Sedimentary Petrology. Wiley-Interscience, New York, pp. 385–407.

Garver, J.I., Royce, P.R., Smick, T.A., 1996. Chromium and nickel in shale of the Taconic foreland: a case study for the provenance of fine-grained sediments with an ultramafic source. J. Sediment. Res. 66, 100–106.

Giles, M.R., 1997. Diagenesis: A Quantitative Perspective—Implications for Basin Modelling and Rock Property Prediction. Kluwer Academic Publishing, Dordrecht. 526 pp.

Gilligan, A., 1919. The petrography of the Millstone grit of Yorkshire. Q. J. Geol. Soc. 75, 251–294.

Goldman, M.I., 1915. Petrographic evidence on the origin of the Catahoula sandstone of Texas. Am. J. Sci. 39, 261–287.

Griffiths, J.C., 1967. Scientific Method in Analysis of Sediments. McGraw-Hill, New York. 508 pp.

Groves, A.W., 1931. The unroofing of the Dartmoor granite and the distribution of its detritus in the sediments of southern England. Q. J. Geol. Soc. 87, 62–96.

Hubert, J.F., 1962. A zircon–tourmalin–rutile maturity index and the interdependence of the composition of heavy mineral assemblages with the gross composition and texture of sandstones. J. Sediment. Petrol. 32, 440–450.

Hubert, J.F., 1971. Analysis of heavy-mineral assemblages. In: Carver, R.E. (Ed.), Procedures in Sedimentary Petrology. Wiley-Interscience, New York, pp. 453–478.

Ibbeken, H., Schleyer, R., 1991. Source and Sediment: A Case Study of Provenance and Mass Balance at an Active Plate Margin (Calabria, Southern Italy). Springer, Berlin. 286 pp.

Ingersoll, R.V., 1983. Petrofacies and provenance of Late Mesozoic forearc basin, Northern and Central California. AAPG Bull. 67, 1125–1142.

Johnsson, M.J., 1993. The system controlling the composition of clastic sediments. In: Johnsson, M.J., Basu, A. (Eds.), Processes Controlling the Composition of Clastic Sediments, Spec. Pap.-Geol. Soc. Am. vol. 284, pp. 1–19.

Johnsson, M.J., Meade, R.H., 1990. Chemical weathering of fluvial sediments during alluvial storage: the Macuapanim island point bar, Solimões River, Brazil. J. Sediment. Petrol. 60, 827–842.

Judd, J.W., 1886. Report on a series of specimens of the deposits of the Nile delta. Proc. R. Soc. 39, 213–227.

Klein, G.DeV., 1963. Analysis and review of sandstone classifications in the North American geological literature, 1940–1960. Geol. Soc. Amer. Bull. 74, 555–576.

Krumbein, W.C., Pettijohn, F.J., 1938. Manual of Sedimentary Petrography. Appleton-Century-Crofts, New York. 549 pp.

Lihou, J.C., Mange-Rajetzky, M.A., 1996. Provenance of the Sardona flysch, eastern Swiss Alps: example of high-resolution heavy mineral analysis applied to an ultrastable assemblage. Sediment. Geol. 105, 141–157.

Ludwig, R., 1874. Geologische Bilder aus Italien. Bull. Soc. Imprim. Nat. Mosc. 48, 42–131.

Mackie, W., 1899a. The sands and sandstones of eastern Moray. Trans. Edinb. Geol. Soc. 7, 148–172.

Mackie, W., 1899b. The feldspars present in sedimentary rocks as indicators of the conditions of contemporaneous climates. Trans. Edinb. Geol. Soc. 7, 443–468.

McLennan, S.M., Hemming, S., McDaniel, D.K., Hanson, G.N., 1993. Geochemical approaches to sedimentation, provenance, and tectonics. In: Johnsson, M.J., Basu, A. (Eds.), Processes Controlling the Composition of Clastic Sediments. Spec. Pap.-Geol. Soc. Am., vol. 284, pp. 21–40.

Meunier, S., 1877. Composition et origine du sable diamantifère de Du Toit's Pan (Afrique australe). C. R. Acad. Sci., Paris 84, 250–252.

Michel Lévy, A., 1878. Note sur quelques minéraux contenus dans les sables du Mesvrin, près Autun. Bull. Soc. Mineral. Fr. 1, 39–41.

Milner, H.B., 1922. The nature and origin of the Pliocene deposits of the county of Cornwall and their bearing on the Pliocene geography of the South-West of England. Q. J. Geol. Soc. 78, 348–377.

Milner, H.B., 1962. Sedimentary Petrography, 4th revised edition: vol. II. Principles and Applications. Allen and Unwin, London. 715 pp.

Molinaroli, E., Basu, A., 1993. Toward quantitative provenance analysis: a brief review and case study. In: Johnsson, M.J., Basu, A. (Eds.), Processes Controlling the Composition of Clastic Sediments. Spec. Pap.- Geol. Soc. Am., vol. 284, pp. 323–333.

Morton, A.C., 1985. Heavy minerals in provenance studies. In: Zuffa, G.G. (Ed.), Provenance of Arenites. Reidel Publ., Dordrecht, pp. 249–277.

Morton, A.C., 1991. Geochemical studies of detrital heavy minerals and their application to provenance research. In: Morton, A.C., Kronz, A., Haughton, P.D.W. (Eds.), Developments in Sedimentary Provenance Studies. Geol. Soc. Lond. Spec. Publ., vol. 57, pp. 31–45.

Morton, A.C., Johnsson, M.J., 1993. Factors influencing the composition of detrital heavy mineral suites in Holocene sands of the Apure River drainage basin, Venezuela. In: Johnsson, M.J., Basu, A. (Eds.), Processes Controlling the Composition of Clastic Sediments, Spec. Pap.-Geol. Soc. Am., vol. 284, pp. 171–185.

Okada, H., 1971. Classification of sandstone: analysis and proposal. J. Geol. 79, 509–525.

Palomares, M., Arribas, J., 1993. Modern stream sands from compound crystalline sources: composition and sand generation index. In: Johnsson, M.J., Basu, A. (Eds.), Processes Controlling the Composition of Clastic Sediments. Spec. Pap.-Geol. Soc. Am., vol. 284, pp. 313–322.

Pettijohn, F.J., Potter, P.E., Siever, R., 1987. Sand and Sandstone, 2nd ed. Springer, New York. 553 pp.

Rahl, J.M., Reiners, P.W., Campbell, I.H., Nicolescu, S., Allen, C.M., 2003. Combined single-grain (U–Th)/He and U/Pb dating of detrital zircons from the Navajo Sandstone, Utah. Geology 31, 761–764.

Retgers, J.W., 1895. Über die mineralogische und chemische Zusammensetzung der Dünensande Hollands und über die Wichtigkeit von Flusz- und Meeressand-Untersuchungen im allgemeinen. Neues Jahrb. Mineral., Geol. Palaontol. 1, 16–74.

Rittenhouse, G., 1944. Sources of modern sands in the Middle Rio Grande Valley, New Mexico. J. Geol. 52, 145–183.

Russell, R.D., 1937. Mineral composition of Mississippi River sands. Geol. Soc. Amer. Bull. 48, 1307–1348.

Schwab, F.L., 1975. Framework mineralogy and chemical composition of continental margin-type sandstones. Geology 3, 487–490.

Seyedolali, A., Krinsley, D.H., Boggs, S., O'Hara, P.F., Dypvik, H., Goles, G.G., 1997. Provenance interpretation of quartz by scanning electron microscope-cathodoluminescence fabric analysis. Geology 25, 787–790.

Siever, R., 1988. Sand. Scientific American Library, HPHLP. New York. 237 pp.

Sircombe, K.N., 1999. Tracing provenance through the isotopic ages of littoral and sedimentary detrital zircon, eastern Australia. Sediment. Geol. 124, 47–67.

Solomon, J.D., 1932. The heavy mineral assemblages of the Great chalky boulder-clay and Cannon-shot gravels of East Anglia, and their significance. Geol. Mag. 69, 314–320.

Sorby, H.C., 1880. On the structure and origin of non-calcareous stratified rocks. Proc. Geol. Soc. Lond. 36, 46–92.

Strakhov, N.M., 1971. Development of lithogenetical ideas in Russia and the USSR: Critical review. Izdatelstvo Nayka, Moscow. 609 pp., in Russian.

Suttner, L.J., 1974. Sedimentary petrographic provinces: An evaluation. In: Ross, C.A. (Ed.), Paleogeographic Provinces and Provinciality. SEPM Spec. Publ., vol. 21, pp. 75–84.

Thürach, H., 1884. Über das Vorkommen mikroskopischer Zirkone und Titanmineralien in den Gesteinen. Verh. Phys. Med. Ges. Wurzbrg. 18, 203–284.

Trowbridge, A.C., Shepard, F.P., 1932. Sedimentation in Massachusetts Bay. J. Sediment. Petrol. 2, 3–37.

Valloni, R., 1985. Reading provenance from modern marine sands. In: Zuffa, G.G. (Ed.), Provenance of Arenites, Reidel Publ., Dordrecht, pp. 309–332.

van Baren, F.A., 1934. Het voorkomen en de betekenis van kalihoudende mineralen in Nederlandse gronden. Ph.D. Thesis, Veenman and Zonen, Wageningen. 120 pp.

Velbel, M.A., Saad, M.K., 1991. Paleoweathering or diagenesis as the principal modifier of sandstone framework composition? A case study from Triassic rift-valley redbeds of eastern North America. In: Morton, A.C., Todd, S.P., Haughton, P.D.W. (Eds.), Developments in Sedimentary Provenance Studies. Geol. Soc. Lond. Spec. Publ., vol. 57, pp. 91–99.

von Eynatten, H., Gaupp, R., 1999. Provenance of Cretaceous synorogenic sandstones in the Eastern Alps: constraints from framework petrography, heavy mineral analysis, and mineral chemistry. Sediment. Geol. 124, 81–111.

von Eynatten, H., Wijbrans, J.R., 2003. Precise tracing of exhumation and provenance using Ar/Ar-geochronology of detrital white mica: the example of the Central Alps. Geol. Soc. London, Spec. Publ. 208, 289–305.

von Eynatten, H., Pawlowsky-Glahn, V., Egozcue, J.J., 2002. Understanding perturbation on the simplex: a simple method to better visualise and interpret compositional data in ternary diagrams. Math. Geol. 34, 249–257.

Weltje, G.J., 2002. Quantitative analysis of detrital modes: statistically rigorous confidence regions in ternary diagrams and their use in sedimentary petrology. Earth-Sci. Rev. 57, 211–253.

Weltje, G.J., Prins, M.A., 2003. Muddled or mixed? Inferring palaeoclimate from size distributions of deep-sea clastics. Sediment. Geol. 162, 39–62.

Weltje, G.J., Meijer, X.D., de Boer, P.L., 1998. Stratigraphic inversion of siliciclastic basin fills: a note on the distinction between supply signals resulting from tectonic and climatic forcing. Basin Res. 10, 129–153.

Zack, T., Kronz, A., Foley, S., Rivers, T., 2002. Trace element abundances in rutiles from eclogites and associated garnet mica schists. Chem. Geol. 184, 97–122.