

# Sedimentary provenance studies

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The study of sedimentary provenance interfaces several of the mainstream geological disciplines (mineralogy, geochemistry, geochronology, sedimentology, igneous and metamorphic petrology). Its remit includes the location and nature of sediment source areas, the pathways by which sediment is transferred from source to basin of deposition, and the factors that influence the composition of sedimentary rocks (e.g. relief, climate, tectonic setting). Materials subject to study are as diverse as recent muds in the Mississippi River basin (Potter *et al.* 1975), Archaean shales (McLennan *et al.* 1983), and soils on the Moon (Basu *et al.* 1988).

A range of increasingly sophisticated techniques is now available to workers concerned with sediment provenance. Provenance data can play a critical role in assessing palaeogeographic reconstructions, in constraining lateral displacements in orogens, in characterizing crust which is no longer exposed, in testing tectonic models for uplift at fault block or orogen scale, in mapping depositional systems, in sub-surface correlation and in predicting reservoir quality. On a global scale, the provenance of fine-grained sediments have been used to monitor crustal evolution.

We introduce below some of the novel techniques which are currently being used in provenance work, and some of the areas in which provenance studies are making, and promise to make, an important contribution to our understanding of earth processes. Many of the techniques and applications are covered by papers collected in this volume. These papers represent a selection of those contributed to a joint British Sedimentological Research Group/Petroleum Group meeting on 'Developments in Sedimentary Provenance Studies' convened by A. C. Morton and S. P. Todd at the Geological Society in June, 1989. In an area as diverse as sediment provenance, it is not surprising that the coverage of papers is incomplete, and we hence include some of the developments and applications which do not appear in this volume, but which also represent frontier areas in the study of sediment provenance. We start this short

review by looking briefly at the framework within which provenance studies are undertaken.

## A requisite framework for provenance studies

The validity and scope of any provenance study, and the strategy used, are determined by a number of attributes of the targeted sediment/sedimentary rock (e.g. grain-size, degree of weathering, availability of dispersal data, extent of diagenetic overprint etc.). For most applications, the location of the source is critical, and ancillary data constraining this are necessary. These data should limit both the direction in which the source lay with respect to the basin of deposition, and some estimate of the distance of transport. In addition, it is important to have some constraint on the degree to which the composition of sediment has been biased away from the original source material(s) by weathering/erosion, abrasion, hydraulic segregation, diagenesis and/or sediment recycling.

Palaeoflow direction may be obtained by judicious use of directional structures, where outcrop is available. In the subsurface, palaeoflow directions may be determined by reconstruction of regional facies patterns using drill core and seismic configuration, together with dipmeter records. A degree of circumspection is necessary when determining palaeoflow as there are instances where this may not be straightforward, even with outcrop data. Low stage fluvial cross-strata may diverge systematically from palaeoslope by up to 90° (Bluck 1976), whilst turbidity currents are often deflected to flow axially with no hint of from where, or from which, flank of the basin margin the sediment was originally shed. Palaeoflow data collected in areas of structural complexity have the additional problem of uncertainties inherent in the structural correction procedure. This is exacerbated in zones of steep or overturned dip, and where rotations about a vertical axis have taken place. As the latter rotations are more commonplace than was previously thought (Kissel & Lau 1989), a

marriage of palaeomagnetic and palaeoflow data may preface future provenance studies in areas of suspected rotation.

In considering the distance to source, the scale of the dispersal system from which the sediment was deposited must be addressed. Some types of depositional environment will be more amenable to this sort of analysis than others. For example, it is unlikely that angular fanglomerates containing labile clasts could have travelled any great distance (> 10 km), but it is difficult to limit the transport scale of dropstones in a tillite. Theoretically, it should be possible to place some numerical limits on scale for alluvial systems, using a palaeohydrological approach. However, in practice, the plan-form and cross-sectional geometry of alluvial channels are often difficult to define precisely (Bridge 1985), and the validity of predictive palaeohydraulic equations for gravels remains uncertain (Reid & Frostick 1987). High sinuosity rivers are more conducive to palaeohydraulic estimation of discharge than are those of low sinuosity, either by an empirical approach (see Ethridge & Schumm 1978 for a critical review) or by employing mathematical models of channel bend flow (Bridge 1978; Bridge & Diemer 1983). Discharge may be related to drainage basin size and stream length (Leopold *et al.* 1964) thus providing some control on sediment transport distance.

Whilst some estimate of transport distance is included in many types of provenance study, others invert the problem and attempt to use the provenance data to limit the transport distance or scale of a dispersal system (e.g. Cliff *et al.* this volume). To use provenance data in this way, an upslope source must retain a similar distribution of lithologies to that present during sedimentation. However, as uplift and erosion expose progressively deeper levels of the source, a different suite of lithologies may be brought to the surface, obscuring source correlations. Linking detritus to source in these instances must consider the configuration of the 'lost' cover, for it may be that source mismatches simply reflect different structural levels of the same source block. This point is developed in the paper by Graham *et al.* (this volume).

Another potential pitfall is the fact that the immediate provenance of most detritus is either a pre-existing sediment or a soil profile, and not bedrock. Climatic factors can exert an important influence on mineralogical and geochemical transformations during soil formation (Singer 1980; Curtis 1990), and on the composition of sediment passed through river drainage basins (Franzini & Potter 1983). These modifications can obscure the ultimate source of the sediment,

but the sediment composition may still be a useful palaeoclimatic indicator. Velbel & Saad (this volume) explore the climatic control on sediment composition by comparing detritus shed from the same source under different climatic conditions (an arid Triassic and a humid Holocene setting).

Sediment recycling can (1) bias the composition towards mature grains which are less amenable to source discrimination; (2) produce complex mixtures involving different sources; and (3) mask the relationship between scale of the dispersal system and the ultimate source of the detritus. Textural and/or petrographic evidence may identify a source in pre-existing sediment e.g. detrital 'cement' grains (Zuffa 1987); broken and re-rounded clasts (Tanner 1976) and textural inversion (Haughton 1989). Zuffa (1987, this volume) provides a useful inventory of features which can be used to distinguish multi-from first-cycle sand grains. Geochronological data can be important in limiting the time available for such recycling.

Subsurface studies have reinforced the significance of diagenesis in modifying detrital grain assemblages (Morton 1984; Milliken 1988, Humphreys *et al.* this volume; Valloni *et al.* this volume). Many of these modifications are now predictable, and mineral assemblages and grain surface textures can be used to monitor diagenetic effects, and to ensure that these are minimized in provenance work.

Lastly, it is worth highlighting an obvious but commonly encountered problem in matching detritus to a prospective source block. Measured attributes for detrital grains (particularly those relating to the newer single grain studies) may provide no new insight unless a comparable dataset exists for the potential source block. Modern stream sediment samples can provide a rapid means of characterising the types of sediment grains expected from a particular basement block (Haughton & Farrow 1989).

## Development of new techniques

Over the last decade, classical petrography (of clasts and sand grains) has given way to an increasingly sophisticated range of geochemical and isotopic techniques. Basic petrography has remained an important tool, particularly in mixed clastic/carbonate or calcarenitic provenance work, and when coupled with the newer techniques in clastic systems (Nelson & DePaolo 1988; McCann this volume; Floyd *et al.* this volume). A quantification of sandstone petrography took place in the 1970s and heralded the

diversification of provenance techniques. A key factor in this quantification was a drive towards using sandstone composition in tectonic discrimination, thus linking sediment provenance to major plate setting (Dickinson & Suczek 1979; Ingersoll 1983). A similar motive drove subsequent attempts to use the bulk geochemistry of sedimentary rocks to look at provenance (e.g. Bhatia 1983). However, tectonic discrimination studies now look set to be eclipsed by techniques which exploit the characteristics of individual grains, rather than bulk populations (see below). This trend towards extracting information from single grains is perhaps the single most important development in recent years, and has been made possible by parallel developments in chemical and isotopic microanalysis.

### *Provenance of conglomerates and breccias*

Conglomerates are particularly useful in looking at sediment provenance in that they provide intact samples of proximal source areas. Clasts thus provide evidence for mineral assemblages which are otherwise lost (or ambiguous) in disaggregated sands. Cuthbert (this volume) shows how pressure-temperature estimates using these clast mineral assemblages can be used to characterize the provenance of metamorphic detritus, and to reconstruct the  $P$ - $T$ - $t$  path for the source block. The geochronology of co-existing minerals can also provide a cooling history for the source uplift and this can be important in assessing whether or not basins were syn-orogenic.

Igneous clasts yield much useful information. Their geochemistry can be used to explore the relationship between various clast types (were they all derived from the same intrusion or volcanic centre?) and to identify the setting of the magmatism (rift, arc, etc.). Leitch & Cawood (1987) and Heinz & Loesche (1988) describe volcanogenic conglomerates which were derived from cryptic volcanic arcs. Igneous detritus can also be used to characterize the deeper structure of the source area, as revealed through inherited zircon grains and isotopic compositions. Geochronological data for clasts can provide a time frame for the magmatism and this is critical to any attempt to infer tectonic setting from petrology of the detritus. A flaw in many conventional petrographic studies is uncertainty as to whether or not the igneous detritus was derived from *coeval* volcanoes or intrusions. Floyd *et al.* (this volume) describe an example of foreland sediments with arc petrographic and geochemical signatures produced by recycling of much older arc terranes. The timing of magmatism in the

source can also be important in the search for displaced source areas (see Haughton *et al.* 1990). New high precision methods of U-Pb dating (e.g. Rogers *et al.* 1989) offer considerable scope for reliable age determinations on clasts. However, Rb-Sr mineral ages for single granite clasts have proved useful (and have been confirmed by U-Pb dating). The use of composite Rb-Sr whole-rock isochrons for groups of clasts is discouraged, as the clasts may not have been co-magmatic, and even if so, may still have had heterogeneous initial Sr isotopic compositions.

Much information may still be derived from the analysis of clast types in the field (see Cuthbert this volume; Graham *et al.* this volume; Garden this volume). Direct evidence for the age of the source can be supplied by fossiliferous clasts (Haughton 1988; Todd 1989). Any analysis of vertical and/or lateral compositional variation should include some assessment of how grain size controls composition. In reconstructing a source area from clasts, attention should be given to how the various clast types might relate to one another. For example, if granite clasts are found in association with sandstone clasts, did the former intrude the latter? Hornfels clasts might have some bearing on this, as might xenoliths preserved within granite boulders. Todd (1989) interpreted clasts of spotted slate and a two-mica, garnetiferous granite as having a source in the aureole and roof of a pluton.

### *Sandstone provenance*

Many of the more recent developments concern sandstone provenance. The high level of interest in this area is mirrored by the predominance of papers dealing with sandstones in this volume. Since sandstones almost invariably comprise mixtures of source materials, sandstone provenance is often best tackled using a range of techniques rather than relying on any one method, an approach emphasized by Humphreys *et al.* (this volume).

Zuffa (this volume) describes recent progress in the petrographic analysis of sandstones (specifically turbiditic arenites) and emphasises that provenance work must go beyond the framework compositions of the QFL approach. Important temporal (coeval versus non-coeval, first cycle versus recycled) and spatial (intra-basinal versus extrabasinal) factors must also be addressed. The value of this approach is evident in studies such as that by Thornburg & Kulm (1987) who show how QFL data do not adequately discriminate modern sand samples from the Chile Trench, demonstrating significant

hydraulic sorting of scoriaceous volcanic grains, and the role of onshore forearc basins in suppressing the supply of volcanic detritus to the trench. Arribas & Arribas (this volume) show that the QFL approach correctly identifies the tectonic setting of the northern Tajo Basin (Spain), but only if calcareous rock fragments are included in the total lithics. Sandstone compositions in the Larsen Basin, Antarctica (Pirrie, this volume) evolve from undissected, transitional and dissected arc provenance to a recycled orogen setting, suggesting unroofing of an arc, but tectonic setting of the northern Tajo Basin (Spain), but only if calcareous rock fragments are included in the total lithics. Sandstone compositions in the Larsen Basin, Antarctica (Pirrie, this volume) evolve from undissected, transitional and dissected arc provenance to a recycled orogen setting. Tortosa *et al.* (this volume) re-examine the use of quartz grain types in provenance analysis, and show that the distinction of plutonic and high grade metamorphic source rocks using the Basu *et al.* (1975) method requires caution.

Conventional heavy mineral analysis has been revitalized by studies of compositional variation within a single mineral species, thus circumventing the detrimental effect of intrastratal solution, often the dominant control on subsurface heavy mineral distribution. Amphibole, pyroxene, epidote, staurolite, monazite, zircon, garnet, spinel, chloritoid, mica and tourmaline are all amenable to this sort of analysis and the development of the approach is discussed by Morton (this volume). Basu & Molinaroli (this volume) explore the use of the opaque heavy mineral phases often disregarded in provenance work. They show that detrital Fe-Ti minerals can retain a provenance record, although no individual character is diagnostic and diagenetic alteration can occur in some instances.

In addition to looking at sediment distribution, specific mineral compositions can have important petrogenetic implications for source areas. Detrital pyroxene and amphibole compositions can be used as petrogenetic tracers in volcanoclastic sequences (Cawood 1983 and this volume; Morris 1988; Styles *et al.* 1989), whilst certain white mica compositions and the presence of glaucophane can identify erosion of high pressure metamorphic rocks (Sanders & Morris 1978). The isotopic composition of detrital mineral grains (using stable and/or radiogenic isotope ratios) can provide additional petrogenetic constraints on source rocks (Heller *et al.* 1985).

Geochemical analysis of sandstones has largely concentrated on tectonic discrimination, following a suggestion by Crook (1974) that

active and trailing margin sandstones might be distinguished on the basis of their  $\text{SiO}_2$  contents and  $\text{K}_2\text{O}/\text{Na}_2\text{O}$  ratios. The advantage here is that geochemistry might allow the tectonic setting of metasediments to be identified despite the loss of original petrographic detail (assuming isochemical metamorphism). More complex multivariate techniques were accordingly developed using both major (Bhatia 1983, Roser & Korsch 1988) and trace element concentrations (Bhatia 1985; Bhatia & Crook 1986). As with all discriminant techniques, the methods are only as good as the data base used to erect them, and problems have been encountered distinguishing sediments from different plate settings e.g. Van der Kamp & Leake (1985). Again, the problem of recycling rears its head. Reworking of older arcs can produce a spurious arc chemistry. McCann (this volume) illustrates the problem of recycling by demonstrating how the provenance of Ordovician-Silurian sediments of the Welsh basin fails to reflect accurately the palaeotectonic setting of the area. An alternative way of utilizing sediment chemistry is the use of specific provenance tracers e.g. the high Cr and MgO contents of sediments with a significant ultramafic source. This approach has been used to trace the original distribution of Caledonian ophiolites with some success (Hiscott 1984; Wrafter & Graham 1989). The geochemistry of modern sands and soils (e.g. Cullers *et al.* 1988) can be used to evaluate provenance signatures in different tectonic and climatic settings.

The geochronology of single sand-sized grains promises to revolutionize the study of sandstone provenance. Three main techniques are currently available: fission track dating of detrital grains; U-Pb dating of U-bearing minor phases e.g. zircon, monazite, titanite; and argon laser probe dating of detrital micas and amphiboles.

Hurford & Carter (this volume) summarize several applications of fission track dating to provenance work. The main limitation of this technique is that the subsequent thermal history of the sediment (following deposition) may reset fission track ages by partial or complete annealing of tracks. Apatite, with its low annealing temperature for tracks ( $<100^\circ\text{C}$ ) is particularly susceptible to this resetting, but detrital zircon (with a closure temperature of  $200\text{--}250^\circ\text{C}$ ) is more likely to preserve original crystallization ages, and consequently has the greater potential for provenance work.

U-Pb dating of single grains has been made possible by the development of low blank, micro-chemical separation procedures (Krogh 1973). When combined with abrasion techniques which minimise the discordance of analysed

grains (Krogh 1982), precise ages may be determined without the interpretative problems posed by the common high discordance of multi-grain or unabraded single grain data. In addition, detrital monazite grains (see paper by Cliff *et al.* this volume) are particularly useful in that they are generally concordant. Cliff *et al.* show how single grain data for zircons and monazites can help to resolve some of the problems posed by multi-grain populations from the same suite of Carboniferous sandstones. Single grains can also be analysed by ion microprobe and it is possible to derive complex multistage histories from single grains and populations of grains in this way (Compston & Pidgeon 1986).

The  $^{40}\text{Ar}/^{39}\text{Ar}$  laser probe also allows dating of a single, or portions of a single detrital grain. A laser is used to ablate a small pit (40–100  $\mu\text{m}$  in diameter) in a grain which has been previously irradiated, and the extracted sample passed to a gas source mass-spectrometer. Kelley & Bluck (1989) present laser probe ages for detrital muscovites and volcanic rock fragments from Lower Palaeozoic greywackes in southern Scotland, identifying a source for the muscovites in an uplifting basement to an arc complex flanking the basin, but a remnant source for at least some of volcanic detritus previously thought to be contemporaneous with deposition.

### *Mudrock provenance*

In spite of being the most abundant sedimentary rock, logistical problems mean that mudrocks have been relatively poorly studied in terms of provenance. In principle, it is possible to study the constituent clay minerals by X-ray diffraction analysis and make some inference of provenance. However, the approach is in practice fraught with difficulties, not least the rapid diagenetic alteration of primary clay mineral species on burial (Humphreys *et al.* this volume). Although the primary mineralogy of mudrocks is easily modified, a useful axiom is to assume that the primary rock chemistry remains unaltered, allowing major, trace and isotopic analyses of mudrocks to discriminate provenance (e.g. Humphreys *et al.* this volume; McCann this volume). Blatt (1985) also recommends that greater attention be paid to the non-clay mineralogy of mudrocks.

Developments in REE and trace element geochemistry, and isotopic techniques, have been particularly important in fine-grained rocks, and have also been widely used in sandstone provenance work. The uniformity of REE patterns in post-Archaeon shales has been used to

estimate the composition of the upper crust, and to contrast this with an Archaeon upper crustal composition revealed by distinct REE patterns for sediments in that era (Taylor & McClennan 1985). Various ratios of the REE, Th, Sc and Co in pelites exhibit secular changes across the Archaeon-Proterozoic boundary and these have been related to a worldwide change in upper crustal composition at this time (Condie & Wronkiewicz 1990).

The uniform REE patterns, implying little fractionation of REE in sedimentary environments, underpins a second development, the use of Sm-Nd model ages to constrain the provenance of mudrocks and sandstones. Significant fractionations of Sm from Nd are thought to occur during addition of material to the crust from the mantle, but not during subsequent reprocessing of this material in the crust. Measured Sm/Nd ratios can thus be used to back correct the Nd isotopic composition (which is controlled by the time integrated decay of  $^{147}\text{Sm}$  to  $^{143}\text{Nd}$ ) until it overlaps with the composition of one of a series of modelled mantle reservoirs. The age of the overlap is a crustal residence age and it is obviously dependent on the type of mantle model used.

From a provenance perspective, several aspects of the procedure are pertinent. First, the residence age returned by a sediment is a *weighted* average of the different source contributions. Petrographic or other constraints on the mixture of various components present may aid interpretation (Nelson & DePaolo 1988; Evans *et al.* this volume; Floyd *et al.* this volume). Secondly, fractionation of REEs, by hydraulic segregation and concentration of heavy minerals or pumaceous lithic fragments may occur in some sandstones (Frost & Winston 1987; McLennan *et al.* 1989) and may bias residence ages. No significant fractionation according to grain-size occurs in other sequences (e.g. Mearns *et al.* 1989). Thirdly, the behaviour of the REEs during diagenesis needs to be further investigated. Milodowski & Zalasiewicz (this volume) identify REE mobilization and fractionation during diagenesis of a mud-dominated turbidite-hemipelagic sequence. Awwiler & Mack (1989) have recently described an apparent diagenetic control on Sm-Nd model ages from the Wilcox Formation in Texas, where sandstones buried at depths of less than 3000 m have model ages of 1.4–1.5 Ga, and those below this level have model ages of 1.5–2.0 Ga. The depth at which this change takes place coincides with the onset of major diagenetic effects, especially dissolution. A similar pattern was noted in the associated shales, but with model ages changing over

depths of 1500–3000 m, coinciding with the illitization of smectite over this interval; (4) crustal residence ages can be relatively insensitive to mixing of young mafic material with older recycled continental detritus (Haughton 1988). Nd data for sediments from the South Island, New Zealand (Frost & Coombs 1989) illustrate the potential for sediment contributions from contemporary mantle additions in active continental margin settings; and (5) the sites at which the REE reside in sedimentary rocks are poorly known. Model ages only constrain the origin of REEs themselves. If REEs are dominantly held in minor phases, the provenance of the bulk of the sediment remains unconstrained.

### Problem-solving using provenance data

The development of these new techniques has widened the scope of provenance studies, allowing more precise source reconstruction/correlation, and opening up new areas in which provenance data can make a contribution. Some of the more important applications are considered briefly below.

#### *Palaeogeography and palaeogeology*

Provenance data can be usefully incorporated in palaeogeographic reconstructions (Allen this volume), particularly in areas of complex tectonics. Heller *et al.* (1985) ruled out the conventional source for turbidites of the Tye Formation, Oregon from the upslope Klamath terrane on the basis isotopic data from detrital minerals. Instead, a provenance from the inboard Idaho batholith was preferred, with the basin originally located much farther east, closer to Idaho. Its present position was achieved during a subsequent history of tectonic rotation. In a second example, Bluck (1983) and Dempster & Bluck (1989) show an incongruity between the provenance of Ordovician sediments now in fault contact with the Dalradian in central Scotland, and the Ordovician history of the Dalradian metamorphic rocks. Despite evidence for rapid uplift of the Dalradian at this time, no detritus of Dalradian provenance reached the flanking Ordovician sediments. What metamorphic detritus there is was shown to have a provenance in a much older Proterozoic belt. Consequently, the Ordovician palaeogeography of central Scotland must include a separation of the Dalradian and the Ordovician sediments.

#### *Strike-slip deformation: timing and scale of displacements*

Provenance data can play a key role in unravelling the history of strike-slip deformation. Provenance mismatches across basin margins can identify structures on which lateral displacements have taken place (Crowell 1982). This is conditional on being able to demonstrate that the mismatch is not merely a product of erosion level (Graham *et al.* this volume). In favourable instances, the distribution of clast types in marginal fanglomerates may be used together with lithosome structure to infer the sense of strike-slip displacement (Ballance 1980; Todd 1989). Displaced source areas can also constrain the scale of displacement (Ross *et al.* 1973), but as large strike-slip faults often trend parallel to regional strike, the resolution may be poor. If the provenance can be tied to subtle lateral differences in the timing of uplift or the nature of the magmatism along the length of a narrow fault-parallel terrane, resolution may be improved. This also applies to using sediment provenance to demonstrate juxtaposition of terranes by establishing transfer of sediment from source to flanking basin across the trace of a major fault (Haughton *et al.* 1990).

#### *Nature of uplift: regional and fault scale*

Although unroofing sequences have been at the forefront of provenance studies since the last century, surprisingly few records of the uplift of regional metamorphic belts have been identified. Modern ideas on the evolution of orogenic belts indicate why this is so. Tectonic erosion by late orogenic extension may excise large crustal sections and can reduce the yield of sediment produced during uplift. Strike-slip displacements are also important in many orogenic belts and these can mean that an unroofing record will not be a simple vertical clast stratigraphy. Instead, different stages in the unroofing process may be preserved at separate strike locations. Orogenic sediment tends to be recycled rapidly through temporary basins which are continually being reworked as deformation propagates towards the foreland, so tending to mask simple unroofing sequences. Lastly, sediment is often transferred through basins close to mountain belts to more distant locations.

The paper by Cuthbert (this volume) illustrates the fragmentary nature of the clastic record of uplift which may be typical of syn-orogenic basins. The Middle Devonian Horneulen basin of Norway records no obvious unroof-

ing history, despite a thick fill which was coeval with uplift. Instead, the basin reveals erosion of lithologies which were at a relatively high level in the orogen, with subsequent displacement on the detachment which generated the basin juxtaposing the sediments against deeper level, high pressure metamorphic rocks whose exhumation to the surface left no clastic record. Miller & John (1988) have also used provenance to trace the history of a basin underlain by a low-angle detachment. In this instance, clast assemblages in a Tertiary basin in SE California reveal the progressive unroofing of hanging wall-rocks to reveal the detachment zone itself, with the youngest sediments derived from both the hanging wall and the footwall.

A useful provenance record can also be obtained from basins in front of, or riding on, thrust sheets. Graham *et al.* (1986) describe an inverted clast sequence in the proximal Laramide foreland basin, and show how sedimentation can be controlled by variable resistance of lithologies progressively exposed in the encroaching thrust sheet. Times at which more resistant lithologies dominate will favour deposition of conglomerates in the basin, whereas erosion of mudstones can suppress conglomerate deposition. Evans & Mange-Rajetzky (this volume) integrate facies, palaeocurrent, heavy mineral and structural evidence to evaluate the provenance of sediments in the Barreme thrust top basin, Hauge-Provence (France), and a record of Alpine metamorphic and structural events is deduced on the basis of these data.

#### *Igneous evolution deduced from provenance record*

A detrital record may be all that remains of some crustal blocks, and of the higher crustal levels of others. Provenance data may thus be the only means of redressing this bias, and can be critical in looking at the evolution of ancient destructive plate margins where often only a partial record of the associated arc magmatism is preserved in situ. A more complete picture of the magmatism may be derived by combining data from igneous detritus with that preserved in what (if any) remains of the arc basement. This has been the case in Scotland, where the Lower Palaeozoic magmatic record south of the Highland Boundary Fault is largely a detrital one. Longman *et al.* (1979) established the presence of an Ordovician magmatic arc in central Scotland on the basis of large boulders preserved in a fore-arc basin. Similarly, Leitch & Willis (1982) interpreted Devonian conglomerates with a

variety of plutonic and volcanic clasts as having a source in the upper levels of a lost volcanic arc marginal to the New England Fold Belt, SE Australia. Cawood (this volume) presents data on mineral grains and volcanic glass from the Tonga arc, showing a uniform, low-K tholeiitic source supplied sediment from the Oligocene to Recent. Nichols *et al.* (this volume) describe unusual sandstone compositions from eastern Indonesia with minimal continental input. Both volcanic arc and ophiolitic source terrains dominate the provenance.

#### *Tectonic setting*

Misgivings about tectonic discrimination based solely on petrographic or geochemical data have already been voiced above and elsewhere (e.g. Girty *et al.* 1988; Mack 1984; Van de Kamp & Leake 1985; Zuffa 1987) and will not be reiterated. The advent of more precise dating techniques for mineral and lithic grains should allow more meaningful tectonic inferences to be made in that it is now possible to identify recycled signatures and to assign precise ages to grains with geotectonic significance.

#### *Crustal evolution*

Fine-grained sediments can sample large continental areas and their provenance has been used to track the evolution of the upper crust through time. Whilst trace-element variations tell us something of the changing composition of the upper crust (see above), isotopic data can constrain the pattern of crustal growth and the importance of sediment recycling. Sm-Nd isotopic data for shales have been used to examine the relationship between time, crustal growth and periods of orogeny (Andre *et al.* 1986; Michard *et al.* 1985; Miller *et al.* 1986). These studies suggest that while orogenies are not always sites of substantial new crustal additions, growth has been episodic with *c.* 90% of the crust existing by the end of the Proterozoic. Veizer & Jansen (1985) use the excess of Sm-Nd residence age over stratigraphic age to predict that recycling is *c.* 90% cannibalistic for the post-Archaean sedimentary mass. Sr isotopic compositions for sediments pose a problem in that  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios for younger sediments are unusually low, given their high Rb/Sr ratios, and the evidence for recycling of older crust. This can be explained by either buffering by the return of Sr to the mantle (Goldstein 1988) or by a secular increase in Rb/Sr of the upper crustal source of clastic

sediments (McDermott & Hawkesworth 1990).

Another aspect of provenance and crustal evolution relates to the earliest preservation of crust. Detrital zircons incorporated in the Jacks Hill Metasedimentary Belt, Western Australia have ages close to 4.2 Ga, older than any so far measured from in-situ crust (Compston & Pidgeon 1986). These imply that parts of the crust existed since this time and were preserved from recirculation through the mantle. The provenance of Archaean sediments can thus provide an important window on the earliest evolution of the Earth's crust.

### *Sediment recycling*

The extent of Phanerozoic recycling means that the distribution of characteristic detrital grains (for instance, grains of zircon of known age) must be sought first in the oldest sediments in which they might be expected to occur, and then in successively younger formations into which the grains may have been recycled. Only then can the provenance of grains in the younger sediments be interpreted. Although single grain studies are still in their infancy, this approach promises to tell us much about the complex pre-history of sediment grains. In the meantime, derived fossils place important constraints on the age of precursor sedimentary sequences. Batten (this volume) shows how reworked plant microfossils can be used to infer derivation from deposits of more than one age or source area, and to constrain the thermal history of the source(s).

### *Analysis of depositional systems*

Sedimentary provenance can be used at a variety of scales to analyse ancient depositional systems. Provenance data can distinguish different alluvial systems in the same basin. Hirst & Nichols (1986) demonstrate a petrographic distinction between two fluvial distributory systems and marginal alluvial fans in the Ebro Basin, Spain. Separate basins may have shared the same antecedent rivers and again this possibility can be explored. Did, for example, large early Devonian rivers in northern Britain supply sediment to coastal alluvial plains in southern Britain (see Haughton & Farrow 1989)? Another problem which can be tackled is the nature of axial drainage in fluvial basins. Were axial rivers fed by transverse rivers or is the axial system antecedent and hence the basin architecture open to hydrological imbalance effects (cf. Blair & Bilodeau 1988)?

Reservoir models can also benefit from a detailed understanding of provenance. Apart from the obvious implications for primary porosity and subsequent diagenesis, sediment compositions can be used to assess sandbody connectivity. Hurst & Morton (1988) use detrital garnet compositions to recognize Ness Formation fluvial sandstones downcutting into the Etive Formation shoreline complex in the Oseberg Field of the northern North Sea, with implications for reservoir simulation. Provenance can also be useful in correlation and Mearns *et al.* (1989) show how Sm-Nd provenance ages display similar vertical patterns in different wells and may be used to correlate barren strata.

### *Climatic implications*

Climate can play an important role in determining the composition of sedimentary rocks and it may be possible to make palaeoclimatic inferences on the basis of provenance data (Velbel & Sand this volume). Climate is particularly important in considering the origin of first-cycle quartz-arenites (Johnsson *et al.* 1988). These are produced where there is intense chemical weathering (generally under tropical weathering conditions) and in environments where such weathering can operate on sediments over an extended period of time. Evidence from coeval palaeosols can be important in assessing the connection between contemporary weathering and resulting sediment composition (Russell & Allison 1985). In fine-grained marine sequences, mineralogical (kaolinite/smectite ratios) and chemical (Th/K ratios) parameters have been used to monitor climate change (e.g. Wignall & Ruffell 1990).

### **Concluding statement**

The London Sedimentary Provenance meeting was timely in that it drew together workers developing and applying techniques which promise to shift the emphasis of provenance work away from tectonic discrimination. Improved petrographic, geochemical and isotopic methods mean that it is now possible to extract a lot more information from sedimentary rocks, and in particular from single grains and clasts. Several contributors stressed the benefit of a multidisciplinary approach, and the value of applying several techniques as part of the same study. We should now be able to achieve a better understanding of how the grain components

which comprise a sedimentary rock were assembled, to reconstruct source areas with greater confidence, and to use provenance data more effectively to test tectonic models.

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