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Geochemical correlation in an exhumed submarine channel complex (Tabernas Basin, SE Spain): comparison to sedimentological correlation at various length-scales

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Abstract

Whole-rock, inorganic, geochemical data have previously been used to aid characterisation and stratigraphic correlation of fossil-poor clastic sedimentary deposits although this approach has not yet been calibrated by testing chemostratigraphic correlations against physical stratigraphic correlations from outcrop. Chemical data from a well-exposed siliciclastic succession in a Tortonian (Late Miocene) submarine slope channel system in the Tabernas Basin of Southern Spain were generated using X-ray fluorescence supplemented by X-ray diffraction, SEM analysis and light microscopy. Amongst the >60 elements measured nearly a quarter of them have proved to be useful or reliable for geochemically-based correlation at the tested scales (~10m, ~50m, ~100m). These elements are SiO$_2$, K$_2$O, Al$_2$O$_3$, CaO, and TiO$_2$, as well as Zr, Nb, Th, Rb, Cs, As, and the Rare Earth Elements; La, Nd, and Ce. High resolution, bed-to-bed geochemical correlation is feasible over short distances (~10m).

Geochemical data from sections in beds that are traceable suggest that a given stratigraphic level seems to be geochemically homogeneous with respect to some key elements.

Geochemical data also provide a useful aid for high resolution sedimentary correlation, at distances of several tens of meters up to at least 100m. Since each individual bed seems to be broadly homogenous in composition, at a larger scale it is be possible to discern a provenance signal within geochemical data. Chemical stratigraphy thus seems to work even in stratigraphically-complicated submarine channel complexes.

Keywords

Sandstone, correlation, geochemistry, sequence stratigraphy, submarine channel system, Tabernas Basin, geochemical correlation, chemostratigraphy
1 Introduction

Biostratigraphy and sequence stratigraphy, two widely used subsurface correlation techniques, are not always robust, especially in fossil-poor deposits, and alternative tools such as petrography and heavy mineral data, palaeomagnetic data or isotope techniques are required (e.g. Preston et al. 1998; Pearce 1999; Ratcliffe et al. 2004). Chemical stratigraphy provides an objective, quick, and relatively low cost method of performing correlation using whole-rock, inorganic, geochemical data. Variations in geochemical characteristics respond to changes in mineralogy, which in turn are controlled by a number of variables, such as: grain size, origin of sedimentary grains, extent of weathering in the hinterland at the time sediments were being created, geochemical processes in the depositional environment, or even diagenesis after deposition if there has been a net import or export of material at the sample scale (e.g. Taylor & McLennan 1985; McLennan 1989; Dypvik & Harris 2001; Garcia et al. 2004). Thus, chemical stratigraphy reflects diagnostic sediment features such as: gross lithology, provenance and sedimentary facies and potentially provides a method for the subdivision and correlation of sedimentary successions.

Chem stratigraphic techniques have been successfully applied to stratigraphic subdivision and inter-well correlation in a range of published cases (e.g., Ehrenberg and Siring 1992; Racey et al. 1995; Preston et al. 1998; Pearce et al. 1999; Hutchison et al. 2001; Ratcliffe et al. 2004, 2006; Friis et al. 2007). In some cases, the results of chemostratigraphy have proved to be ambiguous due to noisy data and consequent lack of consistent patterns and thus not ideal for stand-alone sedimentary correlation (e.g., Andersson et al. 2004; North et al. 2005). Furthermore, published studies of chemical stratigraphy have tended to lack integration with sedimentological and sequence stratigraphic correlation methods. Published test cases of geochemical correlation compared to sequence stratigraphic or sedimentological
interpretation, based on outcrop analyses, are rare. North et al. (2005) examined the validity and limitations of the geochemical approach to high-resolution correlation within fluvial-deltaic successions at the parasequence scale. At the other end of scale, Hussain (2007), attempted to use elemental geochemistry for stratigraphic correlation of two Lower Palaeozoic formations at a distance of over 1250 km.

The single objective of the present study was to test the reliability of geochemically-derived stratigraphic correlations against unequivocal physical correlations of sediments in an exhumed Tortonian (Late Miocene) submarine channel system exposed in the Tabernas Basin, SE Spain (Fig. 1, 2a). Geochemically-derived correlation of wells is typically performed using cuttings samples meaning that petrographic study to support the geochemical correlations is typically limited or absent. In some studies detailed heavy mineral population studies are used to achieve correlation (e.g. Morton et al., 2005); this is quite distinct from geochemical correlation and was not part of this study. Submarine slope channels are major conduits for sediment transport from the hinterland to the deep basin, and typically preserve multiple phases of erosion and filling with axial to margin facies transitions that result in a complicated depositional architecture (e.g. Hodgson et al. 2011; McHargue et al. 2011). Since the detailed applicability, efficiency and resolution of chemical stratigraphic correlations and subdivisions are restricted by the amount of statistical noise in the geochemical signals, this study has investigated bed-scale geochemical variations between physically correlated sections. Geochemical correlations, therefore, have been compared to conventionally-logged and correlated sections at different scales (Fig. 1) to test the application of chemical stratigraphy in the correlation of individual, physically-traceable beds and so address the following specific questions:

(1) What elements and element ratios are best for geochemical correlation?

(2) What controls the geochemical variations in these sediments?
(3) Does geochemical stratigraphic correlation work when compared to physical stratigraphic correlations?

(4) To what degree do geochemical trends follow depositional trends (sedimentary facies and grain size control) and channel axis to channel margin variation, since this potentially reduces the applicability of geochemical data for regional correlation?

(5) Are there distinct geochemical fingerprints for individual beds that allow identification of marker horizons and correlation of sections over distances of several tens to hundreds of metres in channel downstream and channel axis to channel margin direction?

2 Material and Methods

2.1 Geology of the investigation area

The Neogene Tabernas Basin is a small, fault-controlled, intramontane basin resting on the Internal Zone of the Betic Cordillera in SE Spain (Fig. 2a) (Kleverlaan 1987; 1989a; b; Haughton 2000; Pickering et al. 2001; Hodgson 2002; Hodgson and Haughton 2004). It contains a succession of >1 km of predominantly marine sediments in an overall transgressive-regressive succession. The base of the basin-fill comprises Tortonian (Late Miocene) non-marine to shallow-marine conglomerates, which are overlain by deep marine marls with intercalated submarine channel and distributive systems (Kleverlaan 1989a; Pickering et al 2001). Intra-basinal tectonics led to the development of mini-basins and ponded turbidites intercalated with megabeds in the early Messinian (Late Miocene) (Haughton 2000; Hodgson and Haughton 2004). The overlying shallowing upward trend culminates with local deposition of salt associated with the Messinian Salinity Crisis,
followed by formation of an unconformity and fan delta deposition during the Pliocene (Kleverlaan 1989a).

This study focussed on the ‘Solitary Channel’, one of five slope channel complexes of late Tortonian age (Late Miocene) in the Sartenella Formation that are encased in hemipelagic and pelagic bioturbated marlstones with bundles of turbidite beds (Haughton 2000; Pickering et al. 2001; Hodgson and Haughton 2004). The trend of the channel complex has been mapped for at least 7 km along the palaeoflow direction, which is, in part, coincident with the course of a post-depositional fault complex (Pickering et al. 2001; Figure 2b). The westerly, more confined, part of the slope channel complex is composed of at least five different stacked channel units (Fig. 3). The channel-fills preserve a typical fill pattern from basal debrites, through inclined turbidites, to intrachannel, bioturbated, fine-grained deposits, which display evidence of channel back-filling (Pickering et al. 2001) and channel sinuosity (Abreu et al. 2003). Downslope, to the east, the channel becomes less confined (Pickering et al. 2001).

The primary sediment of the channel-fill was derived from the metamorphic ridges of the Sierra de los Filabres (higher metamorphic grade Nevádo-Filabride complex) in the north and the Sierra Gador (lower grade Alpujarride complex) in the west (Fig. 2a), which were exposed in the hinterland at that time (Kleverlaan 1989a). The Nevado-Filabride complex consist of: (1) >5 km of monotonous graphitic mica-schists and quartzite of pre-Permian age, locally intruded by Permian granite (Priem et al. 1966); (2) a Permo-Triassic sequence of metamorphosed feldspathic sandstones and carbonates, and (3) an association of metabasic rocks (of late Jurassic age) and serpentinite slivers, marble and calcareous mica schist (of Cretaceous age) (García-Dueñas et al. 1988). The overlying Alpujarride Complex is separated from the Nevaso-Fliabride complex by the Betic Movement Zone (Platt and Vissers 1980),
and is composed of Permo-Triassic aluminous phyllite and quartzite, and a thick sequence of middle to late Triassic dolomitised platform carbonates.

2.2 Sampling strategies

To study small scale correlations in the submarine slope channel complex using geochemical methods, the erosionally-confined up-stream (westerly) part of the system was chosen (west of the A-92 motorway; Fig. 2b). Here, the channel complex extends for approximately 2 km to the SW from exit 376 of the A-92 motorway, where it passes into the subcrop. In detail, the study area covers outcrops both perpendicular (Rambla Lanujar) and parallel (Campsa) to the palaeoflow direction (Fig. 3).

Sampling was systematically undertaken to test the various hypotheses outlined in the introduction. Samples were collected from vertical sections (pseudo-wells) in order to produce geochemical correlations at a variety of scales for which the conventional stratigraphy was already documented, and traceable in the outcrops. At some locations, access and safety limited sample collection but on average the vertical (stratigraphic) sampling density was three samples per metre. There was no sampling bias by grain size. More than 300 samples were collected from a total of 20 logged sections. In order to avoid alteration effects due to recent weathering at outcrop, concerted effort was made to collect fresh material.

Small-scale geochemical correlations have been tested at Campsa (Fig 3a) and in Rambla Lanujar (Fig. 3b-d) on sections 10 to 15 m apart, by the sampling of individual beds that are physically traceable from one section to the next. Sampling happened, as far as practically possible, at the same vertical position in the same bed. Larger scale correlations within
individual sedimentary units have been tested in Rambla Lanujar (Fig. 3b, d) by sampling of sections within lithostratigraphically-correlatable packages at distances over several tens to hundred metres. Samples were between 100 g and 250 g in order to adequately sample different lithoclasts. In conglomerates with lithoclast sizes exceeding granule to small pebble grain sizes, only the sand to granule sized matrix was sampled in order to avoid significant dilution effects by individual large lithoclasts.

2.3 Analytical techniques

Elemental analysis for chemical stratigraphy was carried out using energy dispersive X-ray fluorescence analysis (ED-XRF). This methodology was favoured due to its high precision and accuracy and its simultaneous analysis of a wide range of elements. The samples were crushed to a fine powder in a tungsten carbide ball mill. Approximately 12g was sub-sampled from each sample. This was then mixed with a wax binding agent that is inert to X-rays and pressed in an aluminium holder, forming a pellet. The analyses were performed using a batch process on a Panalytical Epsilon-5 ED-XRF modified to perform a multi-element scan using a 22 minute analytical program per sample. Sixty one elements were analysed, including ten major oxides (SiO₂, Al₂O₃, Fe₂O₃, MgO, CaO, Na₂O, K₂O, TiO₂, P₂O₅ and MnO), all expressed as a weight percent (wt%). In addition, 33 trace elements (Ag, As, Ba, Bi, Cd, Co, Cr, Cs, Cu, Ge, Hf, Hg, In, Mo, Nb, Ni, Pb, Rb, Sb, Sc, Se, Sn, Sr, Ta, Te, Th, Tl, U, V, W, Y, Zn and Zr), 14 Rare Earth Elements (REEs; La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu), and the halogens, Cl, Br and I, plus sulphur (S), have been determined with results reported in mg/kg (~ppm). The elements S, Cl, Br, Sr, B, Ag and Bi have been excluded from interpretation due to being at or below detection levels in most samples.
All elements analysed by XRF have been calibrated to 25 international standards. As part of the instrument calibration, X-ray intensity was plotted against concentration for each element in each standard, and a relationship determined (generally this is a straight line with an $R^2 > 0.9$). The precision of a given reading varies according to the specific element and concentration. As a general rule, precision is estimated to be better than within 10% for all elements.

Various correlations were attempted starting with simple element and mineral concentration diagrams, and then moving on to a variety of element ratios and indices. Given the vast number of elements analysed there are a very wide number of element ratio options to plot as a function of depth. In this paper we have chosen the concentration and ratio data that best highlight the correlations. To that end, we have here plotted the major minerals and oxide concentrations and the following ratios and indices as a function of depth and compared these to the physically-correlated stratigraphy: $\text{TiO}_2/\text{Zr}$, $\text{SiO}_2/\text{Al}_2\text{O}_3$, $\text{Fe}_2\text{O}_3/\text{K}_2\text{O}$, $\text{Al}_2\text{O}_3/\text{TiO}_2$, $(\text{CaO+Na}_2\text{O})/\text{K}_2\text{O}$.

In order to integrate geochemical data with mineral concentration data, X-ray diffraction analysis (XRD) was performed using a Panalytical X-pert Pro XRD instrument. A copper X-ray tube operated at 40kV and 40mA was used. Powder samples were loaded into cavity holders and rotated continuously during the scan, completing one rotation every 2 seconds. Programmable anti-scatter slits and a fixed mask maintained an irradiated sample area of 10x15mm, with an additional 2° incident beam antiscatter slit producing a flat background in raw data from 3.60°. Scans covered the 2Theta range of 3.66-70.00° over a scan time of 44 minutes and 26 seconds, with 0.02 Rad Soller slits in both the incident and diffracted beam paths. The X'Celerator detector was set to scan in continuous mode with full length (2.122°) active and pulse-height discrimination levels set to 45-80% with a nickel filter employed.
"HighScore Plus®" analysis software and automated Rietveld refinement methods were used with reference patterns from the International Centre for Diffraction Data, Powder Diffraction File-2, Release 2008. XRD mineral quantity data were quantified using the reference intensity ratio technique (Hillier 2003).

For petrographic purposes, a subset of 18 samples was studied by thin section analyses using transmitted, polarised light optical microscopy, backscattered electron microscopy (BSEM) and secondary X-ray analysis (EDAX) using a Philips XL30 scanning electron microscope.

3 Results

3.1 Sedimentary facies

The sedimentary facies of channel axes are dominated by matrix-supported sandy conglomerates and medium- to very coarse-grained sandstone beds, generally <1-m-thick (locally bioclastic). The sediments were deposited by debris flows and high concentration turbidity currents (Haughton 2000; Pickering et al. 2001). Also, clast-supported cobble-grade conglomerates are present, interpreted to represent channel lag deposits from high-concentration sediment gravity flows. The sandstones and conglomerates are predominantly texturally immature, sharp-based, weakly normally graded, and locally bioturbated.

Amalgamation surfaces, indicated by muddy and sandy rip-up clast horizons, are common. Intra-channel thin-bedded marly siltstones and mudstones are preserved towards channel margins (Haughton 2000; Pickering et al. 2001; Abreu et al. 2003), although locally marly silt-prone beds are also interbedded with sandstones and conglomerates in off-axis settings. The siltstones, together with thin-bedded (cm-scale), finer-grained sandstones, were deposited as low density turbidity currents.
3.2 Sedimentary petrography

The sandstone samples are poorly- to moderately-sorted litharenites (Fig. 4a, b). The main detrital components are quartz, fossil fragments (mainly foraminifers, shell fragments), metamorphic lithoclasts (mica schists, quartzites, quartz chlorite schists, and quartzite schists), micas (muscovite together with some paragonite and extensively chloritised biotite), chlorite (greenish chlorite flakes, plus chlorite that has replaced biotite with anomalous blue interference colour of chlorite suggesting a Fe-rich specimen). Transparent accessory minerals (mainly heavy minerals) generally make up less than 1 % of the petrographic composition. They are composed of brownish and euhedral tourmaline, colourless and subrounded zircon, colourless monazite, colourless Ca-Fe-rich garnet, brownish and subrounded rutile, and apatite (with garnet and tourmaline dominating). Broadly, the accessory minerals are uniformly distributed throughout the sandstones either as detrital framework grains or, in the case of zircon and tourmaline, additionally in lithic clasts. The opaque mineral assemblage (≤3 %) consists of Ti-oxides, some with traces of Fe. The opaque Ti-(Fe)oxide grains show subhedral shapes and patchy Ti and Fe distribution (most likely former ilmenite altered to TiO₂ minerals, Pe-Piper et al. 2011 ). Also, skeletal shapes and trellis-like structures occur, which suggest secondary, authigenic TiO₂ formation (Pe-Piper et al. 2011). The sandstones contain a negligible quantity of detrital matrix. Locally, intensely deformed, weak lithoclasts have created pseudomatrix especially in the coarser grained sandstones (e.g. Worden et al. 2000). Diagenetic features also include trace quartz cement overgrowths and the ubiquitous occurrence of calcite cement (5 to >20%).

The fine-grained samples (siltstones and mudstones) are poorly-sorted and contain mica (predominantly muscovite) and chlorite dominating over quartz and fossil fragments (mainly
pelagic foraminifers, shell fragments). Accessory phases are zircon, garnet, apatite, Fe oxides (in part these are haematite pseudomorphs that have replaced frambooidal pyrite), and trace quantities of pyrite only found in the finest-grained samples (Fig. 4c).

A few samples are calcarenitic turbidites composed of well-sorted, sand-sized, siliciclastic (quartz, sparse lithoclasts, glauconite) and calcareous detritus (pellet-like micrite fragments, other carbonate intraclasts, bioclasts (pelagic and benthic foraminifers, shell fragments), sparitic recrystallised detritus), some mixed siliciclastic-micritic matrix and sparitic carbonate cement.

3.3 Bulk geochemical and mineralogy data

The geochemical data from XRF analysis are presented as Table 1. XRD bulk mineralogy data are listed in Table 2. The main minerals present include quartz, muscovite, minor paragonite, chlorite, traces of biotite, calcite and minor dolomite, and locally a small quantity of kaolinite. These geochemical and mineralogical data will now be presented in terms of the stratigraphic context.

3.4 Small-scale (10m correlation) application: individual beds

Small-scale correlations have been tested in three different outcrops by sampling vertical sections within laterally-traceable turbidite beds in down-dip directions, and from channel-axis to channel-margin settings (see Figs. 3, 5). Of the >60 elements measured by ED-XRF, a relatively limited number proved to be useful in stratigraphic correlation, showing identical trends and similar concentrations in traceable beds.
3.4.1 Major element data

Amongst the major elements, silicon and potassium, and to a lesser extent aluminium and calcium, proved useful for correlation purposes. The element concentration data of nearly 140 from 158 samples of the sections in Figure 5, together with XRD mineral data, are plotted against bed number in Figure 6. The good bed-to-bed correlations of SiO$_2$ and K$_2$O are apparently related to the concentration of quartz and muscovite respectively (Fig. 6). Al$_2$O$_3$ roughly follows the K$_2$O trend. CaO shows good correlation with calcite.

Bivariate plots illustrate the linkage between major element data and major host mineral concentrations including all samples considered in this study (>300 samples) (Fig. 7). Scatter indicates that individual elements are not exclusively hosted within one mineral. The good correlation of silica and quartz (Fig. 7a) confirms that the majority of silica is provided by quartz. Alumina concentrations are generally linked to the phyllosilicate fraction although they show some variation with individual phyllosilicate minerals (Fig. 7b). Within the analysed samples major alumina sources are mica (muscovite, paragonite, biotite), and chlorite. The good potassium-muscovite correlation (Fig. 7c) confirms that the main potassium-supplying mineral is muscovite. Calcium concentrations show a distinct relationship to calcite abundance (Fig. 7d), although minor dolomite is also present.

Within the bed-to-bed plots of XRF-defined element concentrations and XRD-defined mineral quantities, there are stratigraphic trend-breaks that can be linked to major changes in lithology (Fig. 6). K$_2$O, muscovite and Al$_2$O$_3$ have their highest concentrations in the finest grained beds. Conversely, SiO$_2$ and quartz are enriched in the sandy lithologies. However, pebbly sandstones show intermediate concentrations for K$_2$O, muscovite and Al$_2$O$_3$ and SiO$_2$ and quartz, reflecting the more lithic content of these sediments (Fig. 8). CaO and calcite
reveal a more complicated pattern, having the lowest concentrations in the very coarse-grained sandstone beds and in the interbedded mudstone horizons, but having higher concentrations in medium-grained packages and their associated mudstones.

SiO$_2$ and Al$_2$O$_3$ concentrations largely reflect grain-size. Al$_2$O$_3$-rich units are phyllosilicate-rich fine-grained lithologies and SiO$_2$-rich units are sand-rich. There is a negative correlation between Al$_2$O$_3$ and SiO$_2$ ($R = -0.46$) which suggests a sandstone-mudstone mixing trend. However, dilution by carbonate may blur this trend. Reappraisal of the data set renormalised to 0% CaO thus leads to a much stronger correlation ($R = -0.92$) (Fig. 9). However, the very coarse-grained sandstones and sandy conglomerates exhibit intermediate concentrations in this mixing trend (Fig. 9), again reflecting the more lithic content of these sediments.

3.4.2 Trace element data

The trace element bed-to-bed correlations are best for are TiO$_2$, Nb, Zr and Th (and Hf to lesser extent) (Fig. 10). In a bivariate plot, Nb exhibits a strong positive correlation with TiO$_2$ ($R = 0.93$, Fig. 11a), both being more abundant in sand- than silt-size fractions. Although Th follows the Zr-stratigraphic variation (Fig. 10), these two elements display a rather poor mutual correlation (Fig. 11b), although both tend to be more abundant in siltstones than sandstones. TiO$_2$ and Zr do not exhibit a simple relationship suggesting that abundances of titaniferous minerals and zirconium bearing minerals do not co-vary, and that they are concentrated in different grain size fractions (Fig. 11c). TiO$_2$ uniformly has the lowest concentrations in the finest grained beds (sandy siltstones) and highest abundances in sandy horizons, with preferential enrichment in medium to coarse sand size fractions (Fig. 8). The highest Zr abundances seem to be preferentially associated with sandy siltstones and fine-grained sandstones, but they also occur in medium- and coarse-grained beds (Fig. 8).
Normalisation of both TiO$_2$ and Zr to Al$_2$O$_3$ excludes the influence of CaO dilution (Fig. 11d). The resulting triangular distribution is typically observed for elements whose abundances are not exclusively explained by sand-silt mixing trends (Garcia et al. 2004). The trends can be explained as mixing lines between different compositional end members: (1) Al-rich siltstones and sandstones with low normalised Zr- and TiO$_2$-concentrations, (2) Al-poor sandstones with a relative TiO$_2$-enrichment compared to Zr, and (3) Al-poor sandstones with a relative Zr-enrichment compared to TiO$_2$.

TiO$_2$ is characteristically found in heavy minerals such as rutile, anatase, brookite, ilmenite, titanomagnetite, titanite. Diagenetic alteration of Ti-minerals is possible (Pe-Piper et al. 2011) but the solubility of Ti is so low that it is unlikely to have undergone any degree of metasomatism. Bulk Ti concentrations thus likely reflect the initial sediment’s Ti concentration and can safely be used for correlation purposes despite Ti-mineral diagenetic reactions. Zr is typically associated with zircon. Whole-rock Zr concentrations are considered to provide a good measure of the zircon abundance in sediments (Preston et al. 1998). From thin section analysis (light microscopy, BSEM and EDAX) TiO$_2$ occurrence in the sandstones can be assigned to detrital rutile grains (negligible to trace amounts) as well as to the opaque fraction (<3 %), which is entirely composed of detrital and authigenic Ti-oxides (most likely former ilmenite altered to TiO$_2$ minerals). EDAX analyses of the mica have confirmed the occurrence of some TiO$_2$ in the mica. The strong positive correlation between Nb and TiO$_2$ (Fig. 11a) suggests that Nb is present as a trace element in detrital Ti-rich minerals. Thorium shows some covariation with Zr (Fig. 10) implying that it must occur either within zircon or is within minerals co-deposited with zircon (Fig. 11b).

A few further elements also provided good bed-to-bed correlation (Fig. 12), including Rb, Cs, and arsenic and the Rare Earth Elements; La, Ce, and Nd.
It is likely that zircon is the dominant host mineral for the REEs in the samples since they correlate with Zr (Figs. 12 1). Furthermore, the REEs could be linked with heavy minerals in the same grain size range as zircon and, for example monazite. The low abundances of REEs in sand fractions can be generally attributed to dilution by quartz. Clay minerals can also have relatively high REE concentrations (Taylor and McLennan 1985; McLennan 1989), so REE enrichment in the mudstones (Fig. 12) may indicate that they sit directly in phyllosilicates.

In the vertical sections (Fig. 12) increasing arsenic abundances are linked to siltstone and mudstone beds, where trace quantities of altered pyrite and Fe oxides have been detected during SEM examination, and which contain abundant mica minerals (Fig. 6). There is negligible correlation of arsenic with bulk iron concentrations (R = 0.23) despite the reported association of As with diagenetically-reduced Fe-compounds and sulphides, such as pyrite (Belzile and Lebel 1986; Moore et al. 1988; Thomson et al. 1998; Bodin et al. 2007).

However, pyrite is only a trace mineral (predominantly below detection in most samples) and Fe is also present in many other minerals (e.g. chlorite, biotite, garnet, Ti-Fe-oxides). The weak positive correlation with both Al₂O₃ (R = 0.53) and K₂O (R = 0.50) thus only implies a linkage of arsenic to silty and muddy sediments (perhaps adsorbed on phyllosilicates; Seddique et al. 2008).

Rubidium seems to be closely associated with K₂O, since it can substitute for potassium in minerals such as alkali feldspars and micas. The good linear correlation of Rb with K₂O (Fig. 13a) suggests it is primarily linked to micas, Cs also follows the rubidium trend implying it is also present in micaceous minerals (Fig. 13b). However, in cross plots K₂O, Rb, and Cs data are distributed in triangles implying addition of two distinct alkaline element-bearing minerals. A possible explanation is the confirmed presence of more than one K-bearing mica
beside muscovites (paragonite) that has a different K/Rb and Cs/Rb ratios to muscovite. The siltstone samples have the highest K$_2$O, Rb and Cs concentrations. The positive correlation of Cs with K$_2$O (and Rb) in sandstone samples probably reflects the mica content in lithoclasts and discrete mica flakes.

3.5 Meso-scale application (50-100m correlation): sedimentological units

Meso-scale correlations have been tested by comparing sections of different outcrops, which represent the same stratigraphic level. At these scales it is not feasible to directly trace individual beds due to outcrop discontinuity. Lithostratigraphic correlation has been used for comparison with chemostratigraphic variations.

In the first meso-scale case study (Rambla Lanujar; Figs. 3, 14), two sections (LNI, LN-G) with similar sedimentary successions and at a distance of about 50 m in the channel down-dip direction have been compared, based on the recognition of stratigraphically-traceable sedimentological trends in the outcrop (Fig. 14a, units 1-5) with unit 5 at the base and unit 1 at the top of the succession. In stratigraphic order (unit 5) sandy pebbly conglomerates (unit 4) laminated medium-grained sandstones interbedded with siltstones (unit 3) dominantly thin-bedded siltstones, (unit 2) laminated medium-grained sandstones interbedded with siltstones and (unit 1) massive coarse to very coarse sandstone beds with interbedded siltstones. The dominant mineralogy and corresponding major elements follow these lithological trends, with elevated quartz and SiO$_2$ concentrations generally occurring in sand-prone units, elevated mica and K$_2$O concentrations in the silt-prone packages. In very coarse-grained sandstones and sandy conglomerates, quartz, SiO$_2$, mica and K$_2$O show intermediate abundances. These trends allow the geochemical identification, characterisation and tracing of the major lithological units (Fig. 14a, units 1-5).
Secondary trends of both individual major and trace elements and element ratios additionally allow subdivision of the major lithological units into geochemically-defined, traceable sub-units (Fig. 14a, subunits a-e). These sub-units are based on vertical trends (upward increasing or decreasing element abundances and ratios), and marker horizons indicated by significant depletions or enrichments of individual elements compared to the same lithologies, e.g.:

- Compositionally very mature sandstone beds with distinct K$_2$O, Al$_2$O$_3$, muscovite and Rb depletion, SiO$_2$, quartz and TiO$_2$ enrichment, very high SiO$_2$/Al$_2$O$_3$ and low Al$_2$O$_3$/TiO$_2$ ratios (e.g. base of 2a, subunit 4c, base of 4e),
- Siltstones with distinct K$_2$O, Al$_2$O$_3$, muscovite, Rb and some Zr enrichment (e.g., top of 2a, in 4b, 4d),
- Siltstones with distinct CaO and carbonate enrichment (e.g., upper part of 3).

In order to mimic drill cuttings in the way they are produced and collected during oil exploration and field appraisal, and to reduce grain-size related noise the dataset was recalculated using a moving average of three samples (Fig. 14b, c). The correlatable patterns identified in Figure 14a are more obvious with the moving average approach and the geochemically based subdivisions are more pronounced. The lithostratigraphic unit 4 represents a very good example. Individual, chemically-defined sub-packages (4a-e) can be traced between both sections by distinct enrichments or depletions of individual elements or minerals, or increasing and decreasing element ratios, respectively.

A second meso-scale case study, also at Rambla Lanujar (Figs. 3, 15), was undertaken using two sections (LN-G-IV, LSIV) also at a distance of about 50 m. As in the previous case (Figs. 14a-c), both sections have a similar depositional trend, but show some variability in lithological composition (Fig. 15). Furthermore, section LN-G-IV lacks vertical continuity related to the outcrop situation. Using a recalculated dataset based on a moving average of
three samples, nevertheless a reasonable geochemical correlation is possible, based on the recognition of traceable major lithologies and geochemical trends:

- the basal coarse clastics (lithostratigraphic unit 4) display high SiO$_2$, K$_2$O, and TiO$_2$ contents, and Zr enrichments at the top,

- lithostratigraphic unit 3 is characterised by decreasing SiO$_2$, K$_2$O, and Zr contents, increasing CaO content, chemical maturity ($\log_{10}[\text{SiO}_2/\text{Al}_2\text{O}_3]$), $\log_{10}(\text{Fe}_2\text{O}_3/\text{K}_2\text{O})$ and TiO$_2$/Zr ratios as well as decreasing Al$_2$O$_3$/TiO$_2$ ratios in the lower part (chemical subunit b) and reverse trends in the upper part (subunit a),

- lithostratigraphic unit 2 comprises a mud-dominated part of the section LSIV that is not accessible in section LN-G-IV, but displays low SiO$_2$, K$_2$O and TiO$_2$ contents, low TiO$_2$/Zr ratios and chemical maturity, high CaO contents and high Al$_2$O$_3$/TiO$_2$ ratios,

- lithostratigraphic unit 1 reflects channel reactivation represented by sand-dominated deposits, which show increasing SiO$_2$, TiO$_2$ and Zr contents and TiO$_2$/Zr ratios; however other elements and ratios display large variability, although the K$_2$O and reverse CaO trend could warrant further chemical based subdivision.

Two additional case studies at Rambla Lanujar considered sections at distances of up to 100 m perpendicular to the palaeoflow direction (Fig. 3, 16). As for Figures 14b-c and 15 the geochemical dataset was recalculated based on an moving average of three samples. The first example (sections LSV, LSVb Fig. 3, 16a) displays two sections in channel unit V (Fig. 3).

Section LSV represents a setting closer to the channel axis consisting of very coarse, pebbly sandstone beds at the base passing into sand-silt-interbeddings and mud-prone beds towards the top. Section LSVb is situated at the northern margin of the channel unit. Here the intrachannel sandstone beds pinch out abruptly forming intercalations in intrachannel mudstone successions. It is possible to trace back an individual, very coarse, thin sandstone bed in section LSVb to the basal coarse clastics of section LSV providing a lithostratigraphic
marker horizon for correlation purposes (lithostratigraphic unit 2 in Fig. 16a, see base of unit V in Fig. 3b). Geochemical data (moving average) display additional trends that allow subdivision and correlation of the overlying sandstone-mudstone interbeddings (subunits a–c of lithostratigraphic unit 1 in Fig. 16a). From base to top these subunits are characterised:

- in subunit c; by lower SiO$_2$ values, increasing CaO contents, decreasing TiO$_2$ and Zr contents, and a higher $\log_{10}(\text{Fe}_2\text{O}_3/\text{K}_2\text{O})$ ratio (compared to lithostratigraphic unit 2)

- in subunit b; by higher contents of SiO$_2$, basal TiO$_2$ enrichment, increasing Al$_2$O$_3$/TiO$_2$ ratio, decreasing chemical maturity and lower $\log_{10}(\text{Fe}_2\text{O}_3/\text{K}_2\text{O})$ ratio,

- in subunit a; in section LSV by additional trends being not represented in section LSVb

The second example of correlation at distances of ~100m (Fig. 16b) displays two sections in channel unit II with section LSIII situated closer to the channel margin and section LNII representing the channel axis (Fig. 3). The sections are located on the eastern (LNII) and western (LSII) Rambla Lanujar river valley with no potential for a physical tracing of lithostratigraphic units. Nevertheless, in both sections overall fining upward is recognisable, which represents decreasing energies during channel fill. Consequently, the axial section LNII is characterised by basal clast-supported conglomerates representing the channel thalweg deposits, followed by very coarse sandstone beds and sandstone-mudstone interbeddings. In section LSIII succession starts with thick basal sandstone beds passing into interbedded sand-mud towards the top. Based on chemostratigraphy and element data (moving average of three samples) subdivision and correlation is possible (subunits a–c in Fig. 16b). From base to top the subunits are characterised:

- in subunit c; by lower SiO$_2$, higher CaO, lower TiO$_2$, low an decreasing TiO$_2$/Zr ratios,

- in subunit b; by higher SiO$_2$ contents, decreasing CaO content, higher TiO$_2$ content as well as TiO$_2$/Zr ratios, and higher chemical maturity,
in subunit a; by lower \( \text{SiO}_2 \) content, increasing \( \text{CaO} \) content, low \( \text{TiO}_2 \) content, increasing \( \text{Zr} \) content, low \( \text{TiO}_2/\text{Zr} \) ratios, high \( \text{Al}_2\text{O}_3/\text{TiO}_2 \) ratios, and low chemical maturity, from subunit c to subunit a an increase in \( \text{Zr} \) content and \( \text{Th} \) content.

The 100m distance between the lithologically correlated sections results in a stronger variability in the lithological composition than for the closer-spaced sections, and a lithostratigraphic correlation between axial and marginal sections is less straightforward. However, element concentration data reflect the overall fining upward trends in individual channel fills (\( \text{SiO}_2 \), \( \text{CaO} \), chemical maturity) and the geochemical data provide correlatable patterns (\( \text{SiO}_2 \), \( \text{TiO}_2 \), \( \text{Zr} \), \( \text{TiO}_2/\text{Zr} \), \( \text{Al}_2\text{O}_3/\text{TiO}_2 \), local chemical maturity and \( \log_{10}(\text{Fe}_2\text{O}_3/\text{K}_2\text{O}) \) ratios).
Amongst the >60 elements measured by ED-XRF nearly a quarter of them have proved to be useful or reliable for geochemically-based correlation at the tested scales (~10m, ~50m, ~100m) for this succession. These elements are SiO$_2$, K$_2$O, Al$_2$O$_3$, CaO, and TiO$_2$, as well as Zr, Nb, Th, Rb, Cs, As, and the Rare Earth Elements; La, Nd, and Ce. The following discussion therefore focuses on these elements.

4.1 Grain size and lithological controls on element abundances

The grain-size dependent relationship with geochemistry is depicted in Figure 9 with low Si/Al ratios in the silt-prone samples and with increased Si/Al concentrations in the sandstones. However, increasing Si/Al ratios do not uniformly reflect increasing grain size, since the coarse and very coarse-grained samples fall between the Al-rich end member and the Si-rich end member. The same holds true for the potassium concentrations. This variability is consistent with the general tendency of coarse-grained fractions concentrating the lithic fragments. This is apparent in thin section (Fig. 4), which reveal coarse schist lithoclast fragments (mica, chlorite), which contribute much Al$_2$O$_3$ and K$_2$O to the most coarse sedimentary rocks (Fig. 8).

In general, argillaceous lithologies contain significantly more abundant and more varied trace element and REE concentrations than interbedded sandstones. Rubidium and Cs are typically enriched in mudstones and siltstones (Taylor 1965; Fralick and Kronberg 1997) and their linear correlations with Al$_2$O$_3$ and K$_2$O reflect the enrichment of mica in the siltstone fraction (Fig. 13).
From the vertical distribution of the Zr concentrations in this study (Fig. 10) it seems that Zr is preferentially associated with the finer horizons. The results suggest the presence of fine-grained Zr bearing phases (enrichment in sandy siltstones and very fine-grained sandstones) and coarser-grained Zr bearing phases (some enrichments in medium- to coarse-grained sandstone beds; Fig. 8). In medium- to coarse-grained sandstone samples, zirconium was found in thin section as small grains (up to 100 µm), but also as silt-sized detrital grains within metasedimentary lithic fragments. This observation supports the conclusion that, with zircon grains rarely exceeding 250 µm (Poldervaart 1955), fine-grained and silty sand represents the most favourable size range for zirconium (Garcia et al. 2004).

The low TiO$_2$ concentrations in the finest beds, and variable concentrations in the sandy lithologies imply that TiO$_2$ is dominated by Ti-heavy minerals rather than occurring as a species sorbed onto clay minerals (Fig. 8). In thin section, TiO$_2$ is linked to the presence of rutile and opaque accessory minerals. Thin section analysis shows that detrital rutile exhibits similar grain sizes to zircon (up to 70 µm). However, TiO$_2$ has a poor correlation with zircon suggesting that they were not co-deposited (see Figure 11). BSEM and EDAX analyses confirmed the occurrence of coarse-grained Ti-bearing opaque grains (up to >500 µm).

Euhedral grains with traces of Fe suggest altered Fe-Ti-oxides (e.g. ilmenite), trellis-like textures and aggregation of several rutile crystals also imply secondary (diagenetic) TiO$_2$–mineral growth (Pe-Piper et al. 2011).

Overall the observed abundances of SiO$_2$, TiO$_2$ and Nb seem to correlate positively with the grain size. In contrast the abundances of Al$_2$O$_3$, K$_2$O, Rb, As, Cs (and to some extent REE) inversely correlate with grain size. Zr and Ca appear to be effectively uncorrelated with grain size.
4.2 Bed-scale geochemical heterogeneities

A distinct difference was found in the element abundances of the sandstones compared to siltstone, mudstones and conglomerates. However, along individual beds a number of elements exhibit negligible or minor variability (see Figs. 6, 10, 12). Thus, the magnitude of intra-bed variation is considerably smaller than the vertical (inter-bed) variation of these elements in a section making them highly favourable for correlation purposes.

The best correlations are exhibited by SiO$_2$, K$_2$O, TiO$_2$, Nb, Th, As, and Rb. Beds are broadly homogeneous for these elements over distances of up to ~20 m (Figs. 6, 10, 12) in both down-flow and axis to margin directions. However even the abundances of Zr (together with REEs) and Cs, and to some degree Al$_2$O$_3$ and CaO, are fairly uniform within individual beds (Fig. 10).

Some of these elements are a good indicator of the dominant detrital mineralogy, such as quartz or mica (SiO$_2$, Rb, Cs, and K$_2$O). Their distribution is controlled by grain size and lithology (i.e., quartz-rich sandstones, phyllosilicate-rich mudstones, lithoclasts-rich conglomerates). Furthermore, compositionally very mature horizons also seem to provide good marker horizons for correlation over distances of up to 50 m and more (Fig. 14). The high maturity relates to sorting processes favouring quartz grains over lithoclasts and micas. Since lithology, grain size and sorting are a function of the energy of the transport medium, so related elements represent the hydrodynamic conditions under which the individual beds have been laid down.
4.3 Depositional trends and geochemical variations

These results have shown that the elements useful for geochemically-based correlations are those whose abundance is controlled primarily by (1) grain size-dependent mineralogy and (2) the heavy mineral content.

TiO$_2$, Zr, Nb, Th, La, Ce and Nd are probably diagnostic of the lithology of the primary source area due to their relative insolubility and immobility during diagenesis and weathering (Taylor and McLennan 1985; Hill et al. 2000), even though e.g. Ti mobility under certain conditions is reported (Pe-Piper et al. 2011) However, at the tested scales their abundance is an expression of varying sedimentary facies and grain size, which cause differences in mineral composition and enrichment of heavy minerals, respectively (Fig. 8).

Coarse metasedimentary lithoclasts, deposited rapidly from high density turbidity currents, contribute notable amounts of SiO$_2$ (from quartzose clasts), TiO$_2$ (altered ilmenite), as well as K$_2$O and Al$_2$O$_3$ (mica schists) and in part CaO (linked either to bioclasts or metacarbonate fragments). The coarsest sediments are most enriched in SiO$_2$ (linked to quartz) or most depleted in phyllosilicate-related elements.

Poorly- to moderately-sorted, normally-graded coarse to medium-grained, massive and planar laminated sandstones (upper flow regime conditions) are characterised by decreasing amounts of SiO$_2$, K$_2$O and Al$_2$O$_3$ in finer sandstones (Fig. 8) resulting from decreasing quantities of large lithoclast fragments. They are also characterised by slightly elevated average TiO$_2$ and Zr concentrations and increasing maximum concentrations in the individual quantities of K$_2$O, Al$_2$O$_3$, and TiO$_2$ (and Nb). Zr and SiO$_2$ with the largest minimum-maximum range in medium-grained sandstones. This is probably caused by differences in individual sorting and...
compositional maturity of individual beds. For example, significant SiO$_2$ and TiO$_2$ enrichment (together with higher Zr concentrations), at the expense of K$_2$O and Al$_2$O$_3$, seem to point to increased compositional maturity. This may be due to (i) alteration and sorting processes during transport, (ii) sorting effects during deposition or (iii) a provenance-related initial supply of more mineralogically-mature sediment. In the last case, a possible shift of sediment source from a lithoclastic source (hinterland) to sediment sourced from a siliciclastic shelf material could account for those changes. In correlations of sections up to several tens of metres in distance (e.g., Fig. 14) these very mature horizons seem to represent reliable marker horizons. The medium to coarse and very coarse-grained sandstones seem to be the favourable grain size fraction for TiO$_2$ enrichment, resulting from the high density of the host mineral as well as a larger initial grain size of the related heavy minerals (opaque Ti oxides, Ti-Fe-oxides). Besides, significant TiO$_2$ enrichments with no direct link to a distinct grain size fraction (e.g. Fig. 16) could indicate provenance-related signals, i.e. the dominant supply of certain clasts (e.g. altered ilmenite) and support the use of geochemical correlation methods.

Siltstones and very fine-grained sandstones (lower flow regime conditions) can easily be distinguished from coarse (upper flow regime) sandstones by their elevated K$_2$O, Al$_2$O$_3$, Rb, Cs and As concentrations, and lower SiO$_2$ concentrations (Fig. 8), which are due to mica enrichment at the expense of quartz. The amount of Rb seems to be a good indicator of the proportion of fine-grained, siliciclastic material present, since elevated Rb concentrations co-vary with the siltstone horizons (e.g. Fig. 12). The fine clastic horizons, furthermore, show higher average and maximum Zr concentrations and a significant decrease in TiO$_2$ concentrations due to grain size differences of the related heavy minerals. The fine-grained clastic horizons also exhibit higher REE and Th concentrations.
Significant enrichments of CaO (30 % up to 60 %) can be attributed to accumulation of predominantly calcareous beds (sandy limestone), composed of siliciclastic and carbonate detritus (quartz grains, peloid micrite fragments, bioclasts) and carbonate cement. Distinct CaO enrichment leads to decreasing amounts of all the other elements under consideration, caused by significant dilution effects and the minor content in siliciclastic detritus. During geochemical correlation of sections ≥100 m apart, and at axis to margin settings, these limestone beds are easily recognisable and traceable. Their occurrence must be linked with provenance signals, i.e., a subtle shift from sourcing sediment from an exclusively siliciclastic source (hinterland as well as shelf) to sourcing sediment from carbonate shelf material.

4.4 Validity of geochemically-based correlations in this study

High resolution geochemical correlation matches lithostratigraphic correlation for closely spaced (~10m) section (Figs. 6, 10, 12). The results presented here show that individual beds seem to be broadly homogeneous for a range of elements, both in down-flow and axis to margin directions over distances of up to ~20 m (Figs. 6, 10, 12). The elements on these figures exhibit negligible or minor variability along single correlated beds. The magnitude of intra-bed variation is considerably smaller than the vertical element (inter-bed) variation in a section. The best correlations are exhibited by SiO$_2$, TiO$_2$, Nb, Th, As, K$_2$O and Rb. However even the abundances of Zr (together with REEs), Cs and Al$_2$O$_3$ and CaO, are fairly uniform within individual beds. North et al. (2005) obtained similar results for Nb, TiO$_2$, and Rb in a deltaic succession. However, in contrast to our study, they reported that Zr has as much variability along a lateral traverse within a single bed as they do vertically through a parasequence.
The elements that permit good bed-scale geochemical based correlations are indicative of (1) heavy minerals (TiO$_2$, Nb, Th, Zr, REEs), or (2) the dominant detrital mineralogy, such as quartz or mica (SiO$_2$, Rb, Cs, K$_2$O). The abundance of these elements is controlled by the hydrodynamic conditions under which the individual beds have been laid down controlling grain size and sorting differences.

At the scale of several tens of metres, geochemical comparison of correlatable packages in lithologically-similar sections (Figs. 14, 15) revealed that major geochemical trend-breaks (here defined as sudden changes in geochemical character of the sediments) can be consistently related to major changes in sedimentary facies (mudstones, sandstones, conglomerates) and are traceable over distances of several tens of metres. This is notable because in these sections the physical tracing of individual beds was not possible due to outcrop discontinuity. Correlation in the field was based on major lithostratigraphic trends and key surfaces (see lithostratigraphic correlation in Figure 14). Furthermore, it seems to be possible to identify grain-size independent, correlatable sub-trends (see chemical correlation in Figure 14), based on the recognition of identical geochemical patterns, minor pattern-breaks or marker horizons with significant enrichments or depletions of certain elements. Despite the occurrence of substantial “noise” related to minor grain size variations, lithostratigraphic correlation was thus improved by using a high-resolution geochemical subdivision of these major lithostratigraphic packages (Fig. 14). Additionally, a recalculation of the dataset using a moving average of three samples (in order to more closely mimic the way drill cuttings are collected and analysed during petroleum exploration and appraisal) more strongly pronounced correlatable elemental patterns between sections. This implies that individual lithological units, at a given stratigraphic level, and locally even individual horizons, are geochemically-correlatable over several tens of metres, even in stratigraphically-complicated systems such as submarine channel complexes.
Since individual beds seem to be broadly geochemically homogenous for the main elements discussed previously, and individual lithological units exhibit a consistent geochemical fingerprint over distances of several tens of metres, it should be possible at larger distances of ~100 m, to separate a geochemical signal (e.g. major changes in composition, provenance) from noise (variability related to grain size differences) using the three-point moving average. With the increased distance between compared sections (up to hundreds of metres) the lithological compositions and sedimentary facies are likely to change significantly (axial to marginal settings) (Fig. 16). However, based on a moving average of element data, signatures such as Ca-enrichment of sandy limestones (carbonate detritus, e.g. Fig. 15, 16a), high compositional maturity (e.g. Fig. 16b), SiO₂ contents (e.g. Fig. 16), or significant Ti-concentrations related to the quantity of opaque Ti-(Fe-) bearing detritus (e.g. Fig. 16b), are generally traceable over distances of up to a hundred metres or more suggest a probable provenance-related signal. The same holds true for element ratios such as TiO₂/Zr, Al₂O₃/TiO₂ and log₁₀(Fe₂O₃/K₂O). Furthermore, depositional trends are reflected in geochemical data trends, such as fining upward tendencies of individual channel fills (SiO₂, CaO, chemical maturity). Geochemical correlation therefore is effective for sedimentary sections ~100 m apart.

8 Conclusion

This study has used an integrated approach involving sedimentology, geochemistry, mineralogy and petrography to test the validity of geochemical correlation with the aid of an outcrop analogue study. Geochemical data have been compared to physical stratigraphic correlations at a variety of scales to determine if geochemical correlations are conformable with the sedimentologically-defined stratigraphic framework.
Amongst the >60 elements measured by ED-XRF nearly a quarter of them have proved to be useful or reliable for geochemically-based correlation at the tested scales (~10m, ~50m, ~100m). These elements are SiO$_2$, K$_2$O, Al$_2$O$_3$, CaO, and TiO$_2$, as well as Zr, Nb, Th, Rb, Cs, As, and the Rare Earth Elements; La, Nd, and Ce.

The geochemical variations in these sediments are controlled by a combination of grain size (for most of the major elements: SiO$_2$, K$_2$O, CaO, Al$_2$O$_3$, Fe$_2$O$_3$, TiO$_2$, but also for the trace elements Zr, Rb, Cs, As) and subtle changes in provenance (for the elements: TiO$_2$, Zr, Th, Rb, Nb, Cs, As, and the REEs La, Nd, and Ce).

High resolution, bed-to-bed geochemical correlation is feasible over short distances (~10m). Geochemical data from sections in beds traceable from outcrop suggest that a given stratigraphic level seems to be geochemically homogeneous with respect to a number of elements: SiO$_2$, K$_2$O, CaO, TiO$_2$, Al$_2$O$_3$, as well as Zr, Nb, Th, Cs, As, and the REEs La, Nd, and Ce. The magnitude of the geochemical variation of these elements within a single bed is negligible, or smaller than the variation vertically through the sections, making them favourable for geochemical correlations. The occurrence and abundance of these correlateable elements are controlled by the dominant mineralogy (quartz, mica, and carbonate) and the heavy mineral content (rutile and other Ti oxides, zircon and related heavy minerals).

Comparisons of the element and mineral data with the lithological data suggest that geochemistry, as well as mineralogy, vary systematically within the sedimentological framework, and that variations are a response to changes in the hydraulic conditions under which individual beds have been formed, causing differences in sedimentary facies (i.e. grain size and sorting). Lateral homogeneity at bed scale implies that the hydraulic conditions must have been fairly consistent over several metres in an individual bed.
Geochemical data provide a useful aid for high resolution sedimentary correlation, at distances of several tens of metre. Since each individual bed seems to be broadly homogenous in composition, at a larger scale it is be possible to separate a provenance signal from noise (variability related primarily to grain size differences) within geochemical data. Distinct element trend-breaks occur at the same positions as major depositional changes.

There is potential to achieve high-resolution correlation based on geochemical data. The occurrence of systematic stratigraphic variations in geochemistry (particular enrichments, depletions or major trends) related to depositional trends allows the recognition of geochemically-distinct subunits in the sections, which can be correlated to lithostratigraphically-comparable and sedimentologically-similar sections.

In stratigraphically-correlatable sections that span distances of hundreds of metres and that exhibit significant changes in the sedimentary depositional pattern, geochemical signals (including SiO$_2$, K$_2$O, CaO, TiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, Zr, Th, Rb) can be traced over these longer distances, permitting correlation at the channel unit scale. Chemical stratigraphy thus seems to work even in stratigraphically-complicated submarine channel complexes.
References


the correlation of continental red-bed reservoirs in the Beryl Field, UK North Sea.


**Figure captions**

Fig. 1: Schematic sketch of a submarine channel system picturing the different scales and directions of correlation attempts tested in this study.

Fig. 2. Location maps of the study area: (a) simplified geology of the Tabernas area in southeastern Spain and (b) course of the studied channel complex and location of analysed outcrops (after: Hodgson 2002, Pickering et al. 2001).

Fig. 3. Studied exposures of the confined slope channel complex with location of analysed sections: (a) in down-dip direction of the channel (Campsa), (b + c) in axis to margin direction of the channel and in different channel units (unit I-V, Rambla Lanujar, height of exposure in b approximately 40 m, see circled group of people for scale) and d) on map of area of Rambla Lanujar.

Fig. 4. Petrography of the major sedimentary facies: (a) Coarse-grained pebbly sandstone, poorly-sorted, with major components being quartz and schist clasts (transmitted light image, XL). (b) Medium-grained sandstones, moderately-sorted, composed of quartz, mica, and opaque as well as transparent accessory phases, calcite cemented (b1: transmitted light image, PPL; b2: BSE image). (c) Sandy mudstone, poorly-sorted, mainly composed of quartz grains and mica flakes in a dense matrix (BSE image).

Fig. 5. Small-scale, single bed correlations in down-flow direction (a) and axis to margin directions (b, c). Sedimentary logs and correlation of the sections (Spacing between sections: ca. 10 m).

Fig. 6. Major element data (XRF) that have proved useful for bed-scale correlation together with their likely host minerals (XRD data). Data were plotted against bed number in the section and compared to the average lithology of each bed (left). The different plots are for different sections (see Fig. 4 for correlation of the sections).

Fig. 7. Cross-plots of major elements (XRF data) and their likely major host minerals (XRD data), with correlation coefficients: a) SiO$_2$ – quartz, b) Al$_2$O$_3$ – muscovite, c) K$_2$O – muscovite, and d) CaO – calcite.

Fig. 8. Box-Whisker plots of the grain size-dependent occurrence of some major and heavy mineral-bound elements.

Key: M – siltstones and mudstones, Sf – fine and very fine sandstones, Sm – medium-grained sandstones, Sc – coarse sandstone, Svc – very coarse to granular sandstones, Gm – matrix-supported sandy conglomerates.

Fig. 9. Cross-plots of the SiO$_2$ and Al$_2$O$_3$ values of the samples from a CaO-free recalculation.

Fig. 10. Bed-wise correlation of primarily heavy mineral bound major and trace elements of the sections in Fig. 4, plotted against bed number in section and compared to the average lithology of each bed (left). Division of Zr and Nb values by ten for plotting data on the same axis as for TiO2 and Th.
Fig. 11. Element relationships of the major heavy mineral bound elements.

Fig. 12. Major, trace and rare earth element data of the sections in Fig. 4, plotted against bed number in section and compared to the average lithology of each bed (left). The different plots are for different sections.

Fig. 13. Element-cross plots of: a) of K\textsubscript{2}O and Rb and b) Cs and Rb.

Fig. 14a. Geochemistry (XRF data) and mineralogy (XRD data) of channel unit I at Rambla Lanujar: lithostratigraphic correlation and geochemical subdivision of sections at the eastern (LNI) and western (LN-G) side of the canyon (spacing between the sections ca 50 m). Correlation is based on major lithological units (units 1, 2, 3…) and chemical defined subtrends (subunits a, b, c…).

Fig. 14b. Moving average of major element data (XRF) and related mineralogy (XRD data) of channel unit I at Rambla Lanujar. Correlation is based on major lithological units (units 1, 2, 3) and chemical defined subtrends (subunits a, b, c). See legend in Fig. 13a for fills of the lithological columns.

Fig. 14c. Moving average of element data and element ratios of channel unit I at Rambla Lanujar. Correlation is based on major lithological units (units 1, 2, 3) and chemical defined subtrends (subunits a, b, c). See legend in Fig. 13a for fills of the lithological columns.

Fig. 15. Moving average of element data and element ratios of channel unit IV at Rambla Lanujar: geochemical based correlative relationship of sections towards the northern (LN-G-IV) and southern (LSIV) margin of channel complex (spacing between the sections ca 50 m).
Correlation is based on major lithological units (basal conglomerates, sandstone-silt-mudstone interbedding) and chemically-defined subtrends (based on element and mineral trends and abundancies, e.g. CaO, TiO$_2$, Zr, element ratios). See legend in Fig. 13a for fills of the lithological columns.

Fig. 16. Moving average of element data and element ratios with assumed correlation of channel axis to channel margin sections of a) channel unit V (e.g. trends of SiO$_2$, CaO, or element ratios) and b) channel unit II (e.g. SiO$_2$, TiO$_2$ content, element ratios) at Rambla Lanujar (spacing between the sections ca 80 - 100 m). See legend in Fig. 13a for fills of the lithological columns.