Tracing low temperature fluid flow on ridge-flanks with sedimentary uranium distribution

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Abstract

Low-temperature, ridge-flank hydrothermal reaction is an important component of heat and chemical exchange. The uranium content of sediments and pore fluids along a ridge-axis to ridge-flank transect perpendicular to the southern East-Pacific Rise is described. Two distinct regions are identified: (1) the ridge-crest (0.36 Ma crust) where significant solid phase U enrichments occur and (2) the ridge-flank (1.9-4.6 Ma crust) with constant
U association with hydrothermal Fe oxide phases in the solid phases and no ongoing in situ reaction of pore fluids with sediments. Upward advection and diffusion of cool, U-depleted basement fluids occurs at many coring sites. At the ridge-crest site the oxic basal fluids strip the plume derived sediment of the excess U, effectively migrating the U upwards through the sediment into the overlying water column. At the ridge-flank sites the pore fluid advection rates are highest at bathymetric/basement highs and advection velocities of up to 7.5 mm yr\(^{-1}\) are inferred from the pore fluid profiles. These estimates are consistent with previous calculations based on fluoride pore fluid distributions. The basal fluid U depletions are in the range 10-70% depending on temperature and redox state and thus low-temperature uptake of U during basalt alteration is a significant sink from seawater. Pore fluid U content is a sensitive tracer of extremely low temperature (<5°C) and low velocity (<10 mm yr\(^{-1}\)) advection through ridge-flank systems and the basal sediment U/Fe ratio is potentially a useful proxy for basement alteration history.

240 words

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1. Introduction

The magnitude and locus of hydrothermal circulation remains poorly constrained in ocean biogeochemical budgets. In particular, a large geochemical exchange flux may be associated with low-temperature fluid flow through mid-ocean ridges and overlying sediments leading to significant chemical exchange with seawater [Maris and Bender, 1982; Nielsen et al., 2006]. This low-temperature exchange at temperatures only marginally above seawater values is extensive in areas of thin sediment cover or topographic highs that penetrate thicker sediment [Fisher et al., 2003; Wheat and McManus, 2008].

Uranium is removed from seawater during high-temperature hydrothermal exchange [Michard and Albarede, 1985] and significant depletion is also seen in low-temperature fluids (62-64°C; [Wheat et al., 2002]) and thus may provide a useful tracer of lower temperature hydrothermal fluid flow. The U content of basalt alteration products in areas of low-temperature hydrothermalism also implies that significant uptake of U occurs during basaltic reaction with circulating seawater [Dunk et al., 2002; Bach et al., 2003; Schramm et al., 2005]. However, relatively little is known about the behaviour and geochemical cycling of U in pore fluids and sediments during low-temperature hydrothermalism in ridge-crest and flank sediments where significant fluid fluxes are inferred to occur with temperature anomalies of 0.1-3.6°C relative to seawater [Nielsen et al., 2006].
Ridge-crest metalliferous hydrothermal sediments contain significant levels of a range of trace metals, with typical U contents in near-vent field sediments of ~10 ppm [Veeh and Boström, 1971; Rydell et al., 1974; Mills et al., 1994; Schaller et al., 2000].

Hydrothermal plume particles scavenge U from the water column via co-precipitation with Fe (hydr)oxides, and have a U/Fe ratio (wt/wt) of ~1.8x10^-6 [German et al., 1991]. Sedimentary U/Fe ratios (~20 x 10^-6) are significantly higher than those reported for oxide plume particulates [German et al., 1991]. The reported 234U/238U activity ratio [Bender et al., 1971; Veeh and Boström, 1971; Mills et al., 1994] of the authigenic component of hydrothermal sediments is within analytical error of the seawater value (1.144; [Chen et al., 1986]), indicating a seawater source for this element.

Sulfidic hydrothermal plume particles can have U/Fe ratios two orders of magnitude higher than oxide dominated systems and the source of U is also inferred to be seawater [German et al., 2002]. Uranium rich sulfides (dominantly FeS2) may be transported to ridge-crest sediments where the fate of the sulfide material depends on the redox status of the sediment and rate of burial [Mills et al., in review]. In near-field hydrothermal mound deposits on the Mid-Atlantic Ridge (MAR) and rise crest sediments on the East Pacific Rise (EPR), observed U/Fe ratios are not constant but show a high degree of variation, ranging from ~20 x10^-6 to > 400 x10^-6 [Mills et al., 1994; Schaller et al., 2000; Mills et al., in review]. Conversely, older sediments (e.g. fully oxidised mound debris on the MAR or far field ridge-flank sediments on the EPR), whilst maintaining a high U/Fe ratio with respect to oxide plume particulates, display a relatively constant, low U/Fe ratio on the order of 20 x 10^-6, suggesting that at least part of the observed U enrichment is a transitory feature [e.g. Mills et al., 1994].
We present new data from the active eastern flank (0-5 Ma) of the EPR at 14-15°S where low-temperature fluid flow is largely controlled by basement topography [Grevemeyer et al., 2002; Villinger et al., 2002]. We sampled the basement fluids by full penetration of the sediment column [c.f. Wheat and McManus, 2008] and demonstrate that oxic fluid flow has a significant impact on the preservation of uranium peaks in the sediment. We demonstrate the successful use of pore fluid U distribution as a tracer of fluid flow in this region of extremely low-temperature, high water-rock ratio flow and propose that basal sediment U/Fe ratios may be used as a proxy for extensive, oxic, low-temperature alteration of the underlying basement.

2. Sampling and Methods

The EXCO study area is a 720km long and 40-90km wide region east of the ridge axis which intersects the ridge axis of the SEPR at 14°14’S, 60km to the south of the Garrett transform fault and north of a minor ridge discontinuity at 14°27’S (Fig. 1). During the EXCO II/2 cruise (January-February 2000) a suite of sediment cores were collected by gravity corer (with a 6m core barrel) from 3 regions overlying oceanic crust with palaeomagnetic ages of 0.36, 1.9 and 4.6Ma (Fig. 1; Table 1). Cores were collected at each site to reflect variations in local bathymetry and heat flow. Cores 12, 17, 19, 20, 24 and 28 sampled basement (i.e. the core catcher was severely dented and basalt was recovered) and thus basement fluid composition can be inferred from the deepest pore fluid compositions [Wheat and McManus, 2008] (Table 1).

Pore fluids were separated by centrifugation of 2-5cm sections of undisturbed sediment core (8-15 samples per core, 30-50 cm depth intervals). All samples were handled at
temperatures <4°C during centrifugation and filtration of the supernatant through Whatman 0.45 μm filters into acid cleaned, polypropylene vials. Sediment samples were taken from the same depth horizon. Sampling artefacts arising from oxic handling of these sediment cores are inferred to be minimal at the low Fe and Mn concentrations observed [Wheat and McManus, 2008]. Eight cores (4 from the 0.36Ma site (core 12, 17, 18 and 19), 3 from the 1.9Ma site (core 10, 20 and 24) and 1 from the 4.6Ma site (core 7)) were selected for bulk sediment digests and a more detailed sequential extraction procedure was also employed on one core (core 12).

0.2 g of dried, ground sediment were digested via a 4 stage procedure; (1) an aqua regia attack (2.5ml), where the samples were refluxed at 90°C overnight and dried down at 100°C; (2) a combined hydrofluoric and perchloric acid attack (HF, 2 ml; HClO₄, 1.5 ml), where the samples were refluxed at 150°C overnight and dried down at 170°C, increasing to 190°C on the observation of white fumes; (3) an HClO₄ attack (2 ml), where the samples were immediately dried down at 190°C; (4) dissolution in hydrochloric acid (6M HCl, 10ml), where the samples were placed in a thermostatically controlled oven at 60°C overnight.

The sequential extraction scheme described by Bayon et al. [2002] was used to separate the sediment (core 12) into four operationally defined fractions: (1) carbonate-bound and adsorbed or readily exchangeable species removed using 10% acetic acid (CAE); (2) acid reducible ‘amorphous’ Mn and Fe (hydr)oxides removed using 1M hydroxylamine/25% acetic acid (AM); (3) organic material removed using 5% hydrogen peroxide (ORG); and
(4) residual material including crystalline iron oxides assessed by complete digestion of the residual phase (RES).

All ICP-AES analyses (Fe, Mn, P, V, Ca, Ti, Al.) were performed on a Perkin Elmer Optima 4300DV instrument. Standards were matrix matched and the RSD of replicate analysis of unknowns was generally better than 2% for all elements presented here. All ICP-MS analyses for U concentration were carried out on a quadrapole mass spectrometer (VG PlasmaQuad 2+ instrument) fitted with an electron multiplier detector. A peak-jumping analytical mode was employed where ion counts were measured at m/z ratios of 235, 236 and 238. 0.5 g of porewater were diluted to a final mass of 5g using 2% (v/v) SBD HNO₃ spiked with a known amount of $^{236}$U. Analytical uncertainty for porewater analyses is estimated to be 10% based on analysis of Pacific seawater. 6 replicate digests and analyses of the USGS MAG-1 standard gave a full method precision of 2.9% RSD for solid phase U analysis.

2.1 Pore fluid modelling

Pore fluid advection velocities can be estimated in short cores (<10m) which are at steady state using the standard one dimensional diagenetic advection-diffusion-reaction equation by assuming that reaction is negligible and that there are no significant changes in porosity or tortuosity with depth [Maris and Bender, 1982]. If we assume that the uppermost measured $[U]_{pw} = C_0$ and that the deepest $[U]_{pw}=C_{base}$ then the solution to the advection-diffusion equation is:
\[ C_z = C_0 + A \left( \exp \left( \frac{v_z}{D_s} \right) - 1 \right) \]

Equation 1

\[ A = \frac{C_{\text{base}} - C_0}{\exp \left( \frac{v_z \tau}{D_s} \right) - 1} \]

Where \( v \) is the advective pore fluid velocity, \( D_s \) is the whole sediment diffusion coefficient for U and \( z \) is depth below seafloor. The whole sediment diffusion coefficient was calculated from the diffusion coefficient at infinite dilution (\( D^0 \)) for temperature and tortuosity. Given the small measured temperature gradient in these cores [Villinger et al., 2002], the sediment temperature (T) was assumed to be constant and equal to the average mid-depth temperature at the ridge-flank 1.9Ma (2.9°C) and 4.6Ma (2.6°C) sites. The diffusivity of U at \( T_{\text{mid-depth}} \) was estimated from the diffusivity at 25°C (4.26 x 10^-6 cm^2 s^-1; [Li and Gregory, 1974] and the Stokes-Einstein diffusion coefficient temperature dependence relationship [Li and Gregory, 1974] scaled for the estimated temperature (T):

\[ \frac{D_{25^\circ C}^0}{D_{0^\circ C}^0} = 2.19 \]

Equation 2

Sediment tortuosity (\( \Theta \)) is estimated from the measured average sediment porosity \( (\phi; 0.72 \text{ at the 1.9Ma site and 0.64 at the 4.6Ma site}) [Boudreau, 1997]\)

\[ \Theta^2 = 1 - \ln(\phi^2) \]

Equation 3

and this is used to correct \( D^0 \) at the \textit{in situ} temperature (T):

\[ D_{s,\text{in situ}} = \frac{D^0}{\Theta^2} \]

Equation 4
DS,T for the 1.9Ma site is 1.33 x 10^{-6} cm^2 s^{-1} and 1.15 x 10^{-6} cm^2 s^{-1} for the 4.6Ma site.

The pore fluid advection velocity (v) was estimated by fitting an advection–diffusion profile to the observed measurement and the best-fit solution was obtained by minimizing the sum of the squares of the residual concentration difference between the observed and estimated [U]_{pw}. No advection-diffusion-reaction modelling was carried out for the pore water profiles indicating significant reaction as the reactions for U are poorly constrained and subject to sampling artefacts.

2.2 Geological setting and pore fluid characterisation

The full spreading rate at the superfast spreading SEPR at 14°14’S is 143-150 mm yr^{-1} [Grevemeyer et al., 2002]. The ridge-crest site at 0.36Ma crust is characterised by smooth terrain and thin sediment cover [Villinger et al., 2002]. Heat flow measurements are significantly below the crustal cooling model predictions confirming that hydrothermal advection of seawater through the thin sediment cover has cooled the basement to temperatures close to that of bottom water (2-3°C; [Villinger et al., 2002]). Both the ridge-crest (0.36Ma) site and the young ridge-flank (1.9Ma) site have lines of abyssal hills which form a series of ridges that run parallel to the strike of the ridge-crest (013°). The 4.6Ma site is between two medium to large sized seamounts [Villinger et al., 2002]. The sediment cover is thin (<3m) on the steep flanks of the northern seamount and increases to >20m between the two seamounts [Villinger et al., 2002]. High heat-flow values measured at the base of the seamount suggest that there is low-temperature discharge in this region. Basalt alteration along the EXCO transect is consistent with
low-temperature oxic to suboxic reactions with measurable uptake of U, Ca and K during alteration [Schramm et al., 2005].

Previous modelling of pore fluid profiles of nitrate and fluoride suggest that there is slow (~mm yr\(^{-1}\)) advective flow through the sediment at ridge-crest and ridge-flank sites at basement highs [Mottl and Wheat, 2000]. Advection-diffusion-reaction modelling of Si data from the 0.36Ma site demonstrate that basalt derived formation fluids are seeping through the thin sediment cover at rates of 10-200 mm yr\(^{-1}\) [Wheat and McManus, 2008]. The formation fluids in the permeable upper oceanic crust are low-temperature, largely oxic and ‘leak’ to the overlying seawater where basement approaches the seafloor or other permeability constraints allow fluid advection [Villinger et al., 2002]. The oxic formation fluids at the 0.36 ridge-crest site have Mg contents indistinguishable from seawater with some loss of Si to secondary minerals during basement reaction [Mottl and Wheat, 2000; Wheat and McManus, 2008]. Reaction with basement and loss of nitrate and fluoride in the formation fluid is seen at the 1.9Ma site [Mottl and Wheat, 2000]. The chlorinity of all formation fluids was within 0.7% of modern seawater implying that the age of the basement fluids is <2000 years at all sites [Mottl and Wheat, 2000].

3. Results

All solid phase sediment data have been corrected for salt content by subtraction of the pore fluid salts estimated from porosity and chlorinity measurements; this correction is negligible for the data presented here (Table 2; Supplementary Tables 1a-c). The carbonate content was estimated from the detrital corrected Ca data and the hydrothermal component by difference (Hydrothermal = Total – carbonate – detrital); [Dunk and Mills,
The carbonate content of EXCO sediments varies from 65-95% [Dunk and Mills, 2006] and the hydrothermal component within the sediment is significant (30-34%) at 140-165 cmbsf for the ridge-crest samples but relatively minor through most of the ridge-flank sediments (<12%). The hydrothermal rich horizon at mid-depth is apparent in all of the ridge-crest cores (Fig. 4) implying a general enrichment in hydrothermal input to this site at this time.

Uranium in the EXCO sediments displays a different behaviour in the ridge-crest and ridge-flank environments with clear excess U present at the ridge-crest sites (Fig. 2). In the ridge-crest region (the 0.36Ma site), the U content of the sediment reaches values of 8-13 ppm in the upper layers of each core sampled and displays a wide range in U/Fe_{ex} (up to ~380 x 10^{-6}). In the ridge-flank environment (the 1.9 and 4.6Ma study sites), the U content of the sediment is low, ranging from 0.2 to 1.4 ppm, and the U/Fe ratio is relatively constant (~30 x10^{-6}). At the ridge-crest site (0.36Ma) the sequential leach data allow partitioning of the U and Fe into 4 operationally defined fractions (Fig. 3; Table 2).

The pore water data for near surface sediments (0-10 cmbsf) consistently display U contents [U]_{pw} lower than seawater values ([U] = 13.9±0.9 nM). There are difficulties associated with the collection of porewater samples for U analysis because of well documented sampling artefacts, most likely due to depressurisation during core collection and precipitation of carbonate which tends to lead to artificially low [U]_{pw} values compared with the seawater value of ~13.9 nM [Toole et al., 1984]. The carbonate alkalinity, Mg and Ca content of EXCO pore fluids was determined onboard during EXCOII/2 and measurements were close to seawater values at all sites [Mottl and Wheat,
indicating that no significant perturbations to the carbonate chemistry are occurring during sampling. Near surface $[U]_{pw}$ values are as high as 12.7 nM at the 4.6 Ma site but much lower (6-9 nM) at other sites. We attribute the non-seawater upper core $[U]_{pw}$ values to significant (1 m+) loss of surface sediment with the 6 m barrel gravity coring technique used which often recovered nearly 6 m of sediment on hitting basement. This is consistent with other tracer measurements (e.g. Fluoride which show significant surface depletions relative to seawater [Mottl and Wheat, 2000].

The observed variation in $[U]_{pw}$ greatly exceeds the estimated analytical uncertainty of 10%, and the maximum $[U]_{pw}$ varied from 9.6 to 29.1 nM. The rapid desorption or oxidation (with subsequent release to the fluid phase) of sedimentary U is a known potential sampling artefact (e.g. [Anderson et al., 1989]). High $[U]_{pw}$ at depth in sediment cores has also been attributed to the transfer of U-bearing sediment particles across a 0.45 μm filter. If either of these artefacts were the cause of the high $[U]_{pw}$ observed in this study, then the greatest effect would be expected in the deeper samples with the highest $U_{bulk}$ and $U_{CAE}$ in the solid phase. This is not observed and therefore we infer that this artefact is not important at this site.

The pore fluid data from the ridge-crest site show the largest range in $[U]_{pw}$ content. The same general profile is seen in the majority of the ridge-crest cores with a minimum at 20-50 cmbsf and a mid-depth maxima at ~150 cmbsf or deeper (Fig. 4). The ridge-flank sites (1.9 Ma and 4.6 Ma) all show depletion of $[U]_{pw}$ relative to the overlying seawater with significant curvature indicative of upward advection and diffusion of a depleted basal fluid at several sites.
The U content of basal pore fluids in ridge-crest cores 12 and 19 situated along the bathymetric high show good agreement at 10.9±0.3 nM and 10.8±0.4 nM respectively. The deeper core 17 basal fluid is closer to seawater composition (15 nM). At the 1.9Ma site two different basal pore fluid compositions were sampled. At the Western site the basal pore fluids are oxic (measurable nitrate, [U]_{pw}=8.3-8.6 nM). At the Eastern site which is situated on a basement high [Grevemeyer et al., 2002] the basal pore fluids are suboxic (zero nitrate, measurable Mn, [Mottl and Wheat, 2000] and the [U]_{pw} for the basal fluid is 4.3 nM. The basal fluid [U]_{pw} at the oxic 4.6Ma site at the base of a seamount is 11.3-11.7 nM. Downcore pore fluid [U]_{pw} profiles for the ridge-flanks sites are compared with model values in Fig. 5 and estimated upward advective velocities are shown in Table 1. There is broad agreement between estimates of upwelling velocity using [U]_{pw} distribution and that estimated from fluoride data [Mottl and Wheat, 2000].

4. Discussion

In the ridge-flank region (1.9 and 4.6Ma crust), U shows a constant linear relationship to Fe, with U/Fe ratios comparable to previously reported values for oxic metalliferous sediments [Mills et al., 1994]. A least squares fit through the U-Fe ridge-flank data gives a U/Fe (wt/wt) ratio of 32 x 10^{-6}. The uniformity of the U/Fe ratio across all samples from the 1.9 and 4.6Ma sites in addition to the basal samples from the 0.36Ma sites suggests a constant association between U and Fe in oxic metalliferous sediments exposed to basal fluid flow. This phase association of U and Fe is assessed through the sequential leach analysis of ridge-crest core 12 which has elevated U/Fe ratios in the upper core and oxic U/Fe ratios near basement (Fig. 3; Table 2).
In core 12, the majority of U was extracted in the CAE fraction (ca. 70-80%; Fig. 3; Table 2). The carbonate material in the EXCO sediments is dominated by calcite (foraminifera and coccoliths). The CAE fraction represents loosely bound or adsorbed U, although given the propensity of U(VI) to form soluble carbonate complexes (e.g. $\text{UO}_2(\text{CO}_3)_2^{2-}$ and $\text{UO}_2(\text{CO}_3)_3^{4-}$) in concentrated carbonate solutions, this fraction may also include soluble U(VI) compounds. Approximately 80-90% of the bulk sediment U in the basal 0.36Ma sample was associated with the CAE fraction (Fig. 3a), implying that the U is dominantly adsorbed to the Fe (hydr)oxide surface as opposed to incorporated into the crystalline structure. This fraction of U, once fixed through adsorption, is assumed to be permanently associated with the Fe, where the $(\text{U}/\text{Fe})_{\text{oxic}}$ ratio represents saturation of surface adsorption sites for U. The similarity in the down core U distribution in each operationally defined leach (Fig. 3a) suggests a pervasive enrichment of U throughout the core, rather than a specific mineralogical association. The excess U inventory ($U_{\text{bulk}} - \text{Fe}_{\text{hydrothermal}}*(\text{U}/\text{Fe})_{\text{oxic}}$) is assumed to be labile during oxic diagenesis and subject to further diagenetic reaction, ultimately leading to loss from the sediment column and a whole core profile displaying a constant, oxic U/Fe ratio.

Heat-flow measurements at the ridge-crest indicates that hydrothermal advection of heat occurs at this site cooling the crust [Villinger et al., 2002]. Pore fluid nitrate profiles indicate an oxic basement fluid at all sites and fluoride profiles indicate no advection at core 12 but significant upward flow (6 mm yr$^{-1}$) at the core 18 site atop an abyssal hill (~3200 m water depth) [Mottl and Wheat, 2000]. The $[\text{U}]_{\text{pw}}$ data indicate that significant
reaction occurs within the sediment column at all ridge-crest sites and no simple
advection-diffusive fit is possible for the data (Fig. 4).

The general decrease observed from the surface sample $[\text{U}]_{\text{pw}}$ to a local minimum at
relatively shallow depths at the ridge-crest site indicates that \textit{in situ} reaction and uptake
of $[\text{U}]_{\text{pw}}$ is occurring in the uppermost part of the core. The solid phase maxima and
$\text{U/Fe}_{\text{ex}}$ maxima coincide with this pore fluid minima (Fig. 4) supporting this inference.
The ridge-crest cores are fully oxic throughout (nitrate = seawater values \cite{Mottl and Wheat, 2000}, therefore a reductive mechanism \cite[e.g.][]{Morford et al., 2009} of removal is
ruled out. Given the high affinity of $\text{U}$ for co-precipitation with Fe (hydr)oxides \cite[e.g.][]{Duff et al., 2002}, this diffusive flux may be driven by adsorption and complexation of $\text{U}$
during oxic alteration of ferrihydrite, rather than a reductive process.

Pore water data for the 0.36Ma site shows a broad $[\text{U}]_{\text{pw}}$ peak at the same depth as the
solid phase hydrothermal peak (Fig. 4). This is attributed to \textit{in situ} oxidation of any $\text{U}$-
rich sulphides to ferrihydrite and alteration of amorphous to more crystalline Fe-oxides
which is inferred to release $\text{U}$ into pore fluids. Under suboxic conditions this $[\text{U}]_{\text{pw}}$ will
coprecipitate with oxide phases and carbonates \cite[Mills et al., in review] but in an area of
active fluid flow supplying oxidants to the base of the sediment column the $[\text{U}]_{\text{pw}}$ will be
remobilised and lost from the sediment over time. At the 0.36Ma site, the basal pore
fluids are oxic with near seawater nitrate concentration and zero Mn in solution \cite{Mottl and Wheat, 2000}. Upwards advection of pore fluids is apparent in the fluoride data from
core 18 (5.8 mm yr$^{-1}$; Table 1) and widespread seepage of basaltic formation fluids has
been inferred from pore water Si profiles \cite{Wheat and McManus, 2008}. The upwards
migration of the solid phase $\text{U}$ is controlled by a mechanism analogous to the burn-down
of oxygen and relocation of sedimentary U in turbiditic sediments [Colley and Thomson, 1985], but where the source of the mobilising fluid is from basement rather than the sediment-water interface. The net effect of the upward diffusion (and advection) of oxygenated fluids is to strip the lower sediments of the excess U inventory (Fig. 4).

Subseafloor U enrichments in SEPR metalliferous sediments along the EPR [Rydell et al., 1974; Schaller et al., 2002] have recently been attributed to enhancement in sulphide (and therefore U) supply to the sediment during Pleistocene glacialis under lower bottom water oxygen conditions [Mills et al., in review]. The primary U enrichment is retained in the sediment during alteration of sulphide to ferrihydrite to crystalline Fe oxides as long as oxidation occurs below the surface mixed layer and no significant oxidation of the deeper sediment occurs during ridge-flank low-temperature fluid flow. On the thinly sedimented eastern flank of the EPR the significant fluid flow relocates the plume derived U from the sediment to the overlying water column.

Pore fluid advection velocity (v) can only be determined where basal fluids have a measurable contrast with overlying seawater values (Fig. 5). Advection of basal fluids depleted in U is apparent at a number of ridge-flank sites associated with bathymetric highs and pore fluid advection rates up to 7.5 mm yr\(^{-1}\) are estimated using the \([U]_{pw}\) distribution. \([U]_{pw}\) appears to be a good tracer of low-temperature (<5\(^\circ\)C) and low velocity (<10 mm yr\(^{-1}\)) fluid advection in the ridge-flank setting. Fluoride has also been shown to be a useful tracer of pore fluid advection in low-temperature systems [Maris et al., 1984] and there is close agreement in the calculated advection velocity estimated from \([F]_{pw}\) and \([U]_{pw}\) data for cores 10, 23 and 24 from the 1.9Ma Eastern ridge-crest site (Table 1) supporting the validity of the estimates from the \([U]_{pw}\) data. This is in contrast
with nutrient profiles which are unreliable at low fluid advection rates [Wheat and McDuff, 1995]. Mg and Ca data at all sites are very close to seawater values minimizing the utility of these classic tracers in this setting.

The concentration of U in basal pore fluids indicates that basement fluids can become significantly depleted in U (ca. 10-70%), even at very low alteration temperatures (<5°C). The extent of U depletion estimated at both the 0.36 and 4.6Ma sites, where basement fluids are oxic with a temperature of ca. 3.0-3.4°C [Villinger et al., 2002], is comparable, with an estimated depletion of 10-20% relative to seawater. At the 1.9Ma site, where fluids are slightly warmer (4.0°C; [Villinger et al., 2002], the extent of U depletion is comparatively higher, with an estimated removal of 35-40% in oxic fluids, and 65-70% in reducing fluids.

Low-temperature alteration processes in the ridge-flank setting are a function of crustal permeability and sediment cover. The small amount of U uptake in EXCO basalts is inferred to be associated with celadonite formation in the upper crust under oxic conditions [Schramm et al., 2005]. The observed uptake of U is low relative to other estimates [Hart and Staudigel, 1982; Kelley et al., 2003]. The lowest basal U content for EXCO formation fluids is 4.3 nM which implies that U uptake from circulating seawater is up to 70% effective at the low-temperatures observed on the EXCO ridge-flank despite the evidence for minimal solid phase uptake of U.

5. Conclusions
Ridge-crest sediments at 15°S on the SEPR display elevated U/Fe ratios typical of MOR near-field sediments which are inferred to be derived from U rich sulphide particles transported by plume dispersal. Basal ridge-crest and ridge-flank sediment have lower near constant U/Fe ratios similar to oxic hydrothermal sediments from other ridge settings (U/Fe = 32 x 10^{-6} wt/wt). In this high fluid-flow environment, oxidation of the ridge-crest sediment column occurs via diffusion and advection of basal fluids through the sediment pile which strips the sediment of excess U which is associated with primary sulphidic hydrothermal inputs and their alteration products. Thus any palaeorecord of past U/Fe distribution is lost from the sediment in areas of active oxic fluid flow. The U/Fe ratio of basal sediments is a potential proxy for low-temperature oxic formation fluids and could be useful in mapping out the distribution of such fluids.

The fitting of a one dimension advection-diffusion model to the pore-water U data confirms that fluids are upwelling along an abyssal hill ridge-crest at the 1.9Ma site and on the steep flanks of the seamount at the 4.6Ma site at rates of up to 7.5 mm yr^{-1}. The removal of U to ocean crust at temperatures close to ambient seawater is an important sink from seawater. These data suggest that pore water U and sedimentary U/Fe ratios could be valuable tracers of both low temperature and low velocity fluid flow in regions away from ridge-crest reaction.

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Figure Captions

Figure 1: Map showing coring locations for this study. The EXCO region is shown and three regions of interest are highlighted. Insets show coring locations within each area.

Figure 2: Inter-element plot for U and Fe in EXCO cores. Crosses are ridge-crest samples (0.36Ma), open circles are ridge-flank samples (1.9Ma) and open triangles are ridge-flank samples (4.6Ma). The dashed line indicates the U/Fe ratio for fully oxic metalliferous sediments [*Mills et al., 1994*].

Figure 3: Sequential leach data for ridge-crest hydrothermal sediments (core 12). Downcore plot of (a) Fe partitioning into operationally defined phases from the sequential leach
data (method adapted from [Bayon et al., 2002]: Dark grey shading (CAE) = carbonate associated and exchangeable Fe, light grey shading (AM) = amorphous Fe oxides and mid grey shading (RES) = residual crystalline Fe. Red line indicates total bulk analysis. and (b) U sequential leach data (shading as for (a)).

Figure 4: Down-core plots of the estimated hydrothermal component (grey shading), pore fluid U content (crosses) and U/Fe solid phase ratio (hatched area) for ridge-crest sites (a) core 12, (b) core 19, (c) core 17 and (d) core 18. Arrows indicate bottom water composition at the EXCO site; seawater values are approached at the core top and near basement.

Figure 5: Down-core pore fluid U content for the ridge-flank 1.9Ma (West and East) and the 4.6Ma sites which show upward advective flow. 1.9Ma West: open squares = core 20, closed triangles = core 21, 1.9Ma East: open circles = core 24, closed circles = core 10, crosses = core 23, 4.6 Ma: closed triangles = core 7, open circles = core 4, crosses = core 25, closed circles = core 26, open squares = core 27. Dashed lines show the advection-diffusion model fits through each data set (see text).
Dunk and Mills, Figure 1
Sequential Leach
Fe (mg g\(^{-1}\))

0 40 80 120

0 4 8 12 16

Sequential Leach
U (µg g\(^{-1}\))

Depth (cmbsf)
Table 1: Core locations, basement U content and estimated upwelling velocity

<table>
<thead>
<tr>
<th>Crustal Age</th>
<th>Core</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Water Depth</th>
<th>Basement U nM</th>
<th>upwelling velocity mm yr(^{-1}) nM</th>
<th>RMSD</th>
<th>#upwelling velocity mm yr(^{-1}) mM</th>
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<tr>
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Seawater 13.9

# = calculated from fluoride profiles (Mottl and Wheat, 2000)
Table 2: Sequential leach analysis of core 12

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<th>CAE (mg g(^{-1}))</th>
<th>AM (mg g(^{-1}))</th>
<th>ORG (mg g(^{-1}))</th>
<th>RES (mg g(^{-1}))</th>
<th>Sum (mg g(^{-1}))</th>
<th>Bulk Fe (mg g(^{-1}))</th>
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<th>Depth (m)</th>
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<th>AM (μg g(^{-1}))</th>
<th>ORG (μg g(^{-1}))</th>
<th>RES (μg g(^{-1}))</th>
<th>Sum (μg g(^{-1}))</th>
<th>Bulk U (μg g(^{-1}))</th>
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</table>

* = leach not determined and therefore component estimated by difference

CAE = carbonate and adsorbed elements, AM = amorphous Fe oxides, ORG = organic phases and RES = residual
Sum = CAE + AM + ORG + RES