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Turbidites provide a unique opportunity to study diagenetic processes[1]

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Abstract

The sedimentary record has always been affected by both diagenesis and changes through time in the input flux. It will be shown that distal turbidites, which are extremely uniform throughout upon emplacement, can be used to constrain diagenetic processes. Emplacement of turbidites causes the exposure of various labile and reduced components to oxic pelagic conditions. This initiates various diagenetic processes such as organic matter decomposition, element redistribution and carbonate dissolution. The influence of these processes on the sedimentary record can be obtained directly from depth profiles within initially homogeneous turbidites. The sedimentary record can provide strongly biased information when diagenetic alterations are not considered.

Introduction

In recent sediments, profiles showing concentration or abundancy versus depth are usually interpreted in terms of changes through time at the site of deposition or in terms of diagenesis. In this paper, diagenesis refers to all physical, biological and chemical processes that occur during and after deposition of sediments. If diagenesis is absent, then variations in components with depth are connected directly with fluctuations in the composition of the depositional flux. The assumption of very limited or no diagenesis is implicit in the use of concentration (and also abundance, activity and intensity) versus depth profiles in studies of paleoceanography, provenance and stratigraphy. If fluctuations through time in the depositional flux are absent, then all changes in the composition or characteristics with depth are due to diagenesis. This is the hypothesis underlying the concept of steady-state diagenesis which has provided a good description of most early-diagenetic conditions (e.g. Berner 1980).

In nature, most sedimentary components are influenced both by diagenesis and by the variability in the depositional flux. Some components, such as the dissolved oxygen content are largely determined by diagenesis, whereas others, such as the minerals zircon and ilmenite, mainly reflect variations in the depositional flux. For most components, however, there is no a priori information regarding the importance of historical input and diagenetic variability. Nevertheless such information is of the utmost importance for the use of the sedimentary record in paleoceanographic, stratigraphic and diagenetic studies.

In this context, interbedded pelagic and turbiditic sediments as found in the Madeira Abyssal Plain (MAP) are very interesting. In the MAP, pelagic

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sediments (accumulating at a rate of 0.5 to 1.0cm/ka) are interrupted sporadically by turbidite units (Weaver & Thomson 1987, Schüttelhelm et al. 1989, Middelburg & Nakashima 1992). A remarkable feature of these distal turbidites is their homogeneity upon emplacement. Concentration versus depth profiles within these turbidites can therefore be interpreted in terms of post-depositional changes only. In this paper, I will present a short, necessarily incomplete, overview of the diagenetic processes occurring in turbidites of the MAP, with the purpose to show the potential that diagenetic processes have to modify the sedimentary record.

Madeira Abyssal Plain turbidites

Late Quaternary sediments in the MAP consist of alternating thick (up to 6m) distal turbidites and thin (centimetre to decimetre) pelagic units. Individual turbidites are easily recognized by their distinctive colours and lithology and have been lettered from the top downward (Weaver & Kuijpers 1983). The basal layers are generally graded and vary from several centimetres to tens of centimetres in thickness. They are overlain by thick (up to 6m) ungraded muds. The transition from graded silt to uniform mud is fairly abrupt, occurring over 5cm. It has been proposed that these ungraded muds have been deposited from high-density non-turbulent turbidity currents (McCave & Jones 1988).

The uniformity of these muds is shown by several parameters: modal sizes, median and percentage silt (Weaver & Rothwell 1987, McCave & Jones 1988), coccolith floras (Weaver & Kuijpers 1983), mineralogy (Pearce & Jarvis 1992) and geochemical composition (Jarvis & Higgs 1987, De Lange et al. 1987, Middelburg & De Lange 1988, Thomson et al. 1988). Important for the present discussion is that these ungraded muds have a constant chemical composition throughout upon emplacement.

On the basis of geochemical and mineralogical characteristics which reflect their source area, three major turbidite types can be recognized in the MAP: organic-rich, volcanic and calcareous turbidites (De Lange et al. 1987, Middelburg & De Lange 1988). The organic-rich turbidites are derived from the NW African margin and contain more than 0.3% C_{org}, about 50% carbonate, and sometimes large amounts of biogenic silica. The original sediments on the NW African margin which give rise to organic-rich turbidites have accumulated more rapidly than the pelagic sediments in the MAP. As a consequence, the former sediments have preserved relatively high concentrations of labile components such as reactive organic carbon and biogenic silica, and have experienced sulphidic conditions which resulted in the formation of iron sulphides. The emplacement of such a turbidite causes the exposure of various labile and reduced components to oxic pelagic conditions. Most of these components will then react to accommodate to their new environment. In such circumstances oxidation/reaction fronts may develop and progress downward (Colley et al. 1984, Wilson et al. 1985, 1986).

Diagenetic processes following emplacement of turbidites

The emplacement of a turbidite is followed by deposition and rapid consumption of oxygen and nitrate originally present in pore water, owing to the presence of appreciable labile organic matter and other reduced components. Oxygen and nitrate from bottom water then diffuse into the turbidite creating a reaction front at which redox reactions are localized (Fig. 1). The reaction front deepens the upper oxidized layer by propagating downward at a rate determined by the reducing capacity of the sediment and the balance between diffusive fluxes of oxidants (oxygen and nitrate) and reductants (manganese(II) and iron(II)). In sediments the progress of this reaction front is marked by a sharp colour contrast from brown to olive-green (Fig. 1). This burning-down phenomenon results in the formation of a partially oxidized turbidite, with oxic sediment overlying suboxic (neither oxygen nor sulphide) sediments. The deposition of the next turbidite causes the diffusive flux of oxidants to cease and as a result the downward penetration of the oxidation front will cease as well (Colley & Thomson 1985, Colley et al. 1989). Relict fronts are generally

marked by colour changes from brown to olive-green or from pale-green to dark-green depending on the calcium carbonate content and age of the turbidite.

The extent and depth to which this oxidation front has affected the initally homogeneous turbidite depend on the time period it has been active, the permeability and composition of the sediment and the oxygen content of the bottom water (Thomson et al. 1987, Buckly & Cranston 1988). For instance, the difference in organic carbon contents between the oxidized and the unoxidized sections of turbidites is related to the time period during which the oxidation front has been active. For the most recent turbidite **a**, where the reaction front has been active for 500 years, about 30% of the organic matter has been oxidized (Colley et al. 1989), whereas for older turbidites (e.g. turbidites **e** and **f**), where fronts have been active for tens of thousands of years, up to 80% can be degraded and lost (Colley et al. 1989, Prahl et al. 1989).

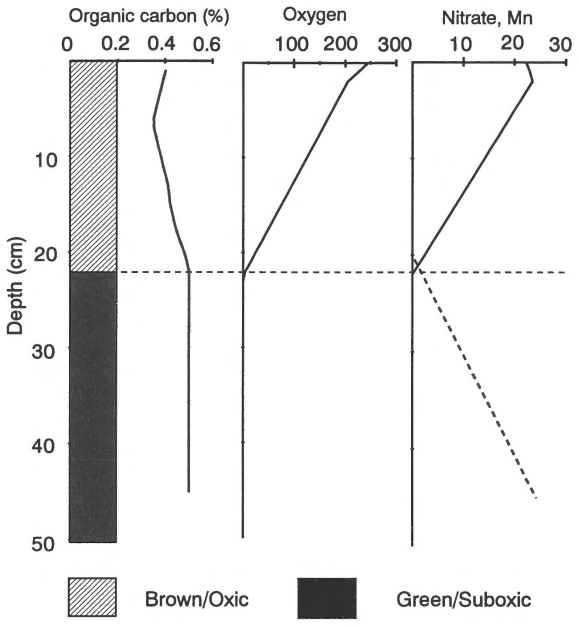

Fig. 1. Idealized distribution of solid-phase organic carbon and pore-water oxygen, nitrate (solid line) and manganese (dashed line) in a recently emplaced turbidite based on boxcore data presented by Wilson et al. (1985, 1986) and Thomson et al. (1987). All dissolved concentrations are given in micromole per dm^3. Notice that the maximum depth of the reaction front (indicated by the horizontal dashed line) corresponds with a colour change in the sediment from brown to green.

Diagenetic effects on organic matter

Organic matter is usually considered to be a composite of residual materials derived from marine and terrestrial sources. Differentiation of marine and terrestrial organic matter input is usually based on microscopic, elemental, isotopic, and molecular biomarker parameters. For instance, marine organisms have C/N ratios ranging from 6 to 8, while land plants generally have ratios higher than 12. Similarly, marine organic carbon is isotopically heavier ($\delta^{13}C_{org}$ −18 to −23‰) than most terrigenous organic carbon ($\delta^{13}C_{org}$ −24 to −29‰). The organic compounds (with different C/N ratios and isotopic values) that make up organic matter vary in their susceptibility to decomposition (Middelburg 1992). It has been shown that the microbial community tends to utilize substrates sequentially, the more reactive substrates being consumed first (Tegelaar et al. 1989). As a consequence of the preferential utilization of specific compounds, the composition of organic matter, as revealed by C/N ratios, isotopic values or molecular biomarkers, changes considerably during decomposition. Nevertheless, most researchers distinguish between organic matter of marine origin and organic matter of terrestrial origin in order to obtain paleoceanographic information. How reliable is this approach?

A comparison between the organic matter characteristics of the oxidized upper and unoxidized lower parts of initially homogeneous turbidites may be useful, because any difference must be related to diagenetic changes. The relevant data have been published by De Lange (1988, 1992), Scholten (1991) and Prahl et al. (1989) and a selection is presented in Table 1. Oxidation of the sediment caused a decrease in both organic carbon and nitrogen of about 80 and 70% respectively. It also caused a shift in C/N ratios from 9.2–11.3 to 7.0 and in $\delta^{13}C_{org}$ values from −20.2 to −23.0. Interpretation of these results without consideration of early diagenetic modification would lead to erroneous conclusions. The change in $\delta^{13}C_{org}$ values could be interpreted as change toward a higher terrestrial organic matter

input, since terrestrial organic matter usually has more negative $\delta^{13}C_{org}$ values than marine organic matter. In contrast, the shift in C/N ratios would indicate a change toward marine organic matter, because marine organic matter normally has lower C/N ratios than terrestrial organic matter.

These significant changes in the composition of organic matter during decomposition may seem to be an extreme example, because about 80% of the original organic matter has been destroyed. However, one should realize that in pelagic environments normally more than 90% of the organic matter supplied to sediments is readily degraded and only a few percent becomes permanently buried and is thus available for paleoceanographic studies (e.g. Emerson & Hedges 1988). Therefore, any distinction between organic matter sources based on the modified organic matter remaining after decomposition will be biased. Future studies on the organic matter characteristics of oxidized and unoxidized parts of turbiditic sediments may perhaps shed light on this important problem.

Post-depositional mobility of trace elements

Many trace elements are redistributed in response to oxidation-reduction cycles in sediments. For multivalent elements, the oxidized and reduced forms may show different solubilities or affinities for solid phases. Some other elements may be adsorbed by or co-precipitated with phases that are involved in redox transformation such as Fe and Mn oxyhydroxides (Salomons & Förstner 1984). Hence, various trace elements may show post-depositional mobility in response to redox changes. In principle one could study redox cycles in sediments that accumulate continuously, but one always has to be aware of historical input fluctuations of the element being studied. This uncertainty in the interpretation of post-depositional mobility can be excluded by studying redistribution of elements within a turbidite unit.

Figure 2 shows the distribution of Ti, Y, U and V surrounding the relict redox boundary in turbidite **f** of the Madeira Abyssal Plain. Titanium and yttrium are elements that are not involved in redox transformations, and their geochemistry is consequently uniform within the turbidite. Uranium and vanadium both peak below the redox boundary. These characteristic depth profiles of U and V have been identified in various turbidites (Colley et al. 1984, 1989). The U profile is the result of uranium (VI) mobilization in the top as a result of bottom-water oxidation. This oxidized uranium fraction then diffuses from the top of the unit and becomes immobile by reduction to U(IV) in the immediately underlying suboxic sediment. For vanadium a similar mechanism may be operating since the lower valencies of vanadium are less soluble than pentavalent vanadium. These enrichments of U and V must be related to post-depositional mobility since initial concentrations were uniform.

Turbiditic sediments from the North Atlantic Ocean have also been used to identify the post-depositional mobility of platinum, iridium and rhenium in marine sediments (Colodner et al. 1992). Figure 3 shows measurements of Pt, Ir and Re in a partially oxidized turbidite. The oxidized and unoxidized sections of this turbidite are separated by a transition zone. Platinum is enriched in a broad peak toward the base of the transition zone. Rhenium is, like U and V, enriched below the redox boundary in the unoxidized section. The behaviour of iridium is

Table 1. Comparison between oxidized and unoxidized sections of the f-turbidite from the Madeira Abyssal Plain; approximate age 73–127 ka (data from Scholten 1991)

Interval	Depth (cm)	Organic C (wt%)	Organic N (wt%)	C/N molar ratio	$\delta^{13}C_{org}$ ‰
Oxidized	704–714	0.22	0.036	7.0	−23.0
Unoxidized	751–761	1.04	0.107	11.3	−20.2
Unoxidized	772–782	1.00	0.127	9.2	−20.1

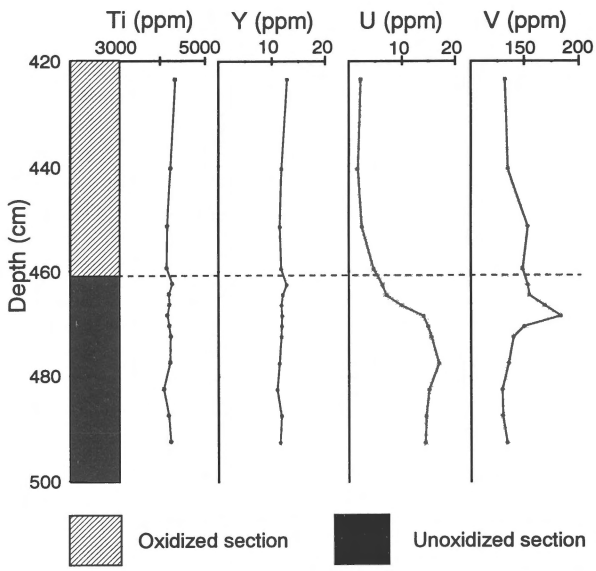

Fig. 2. Geochemical profiles of Ti, Y, U and V over the relict redox boundary (colour change) in the upper part of the f-turbidite (approximate age: 73–127 ka). All concentrations are shown on a carbonate-free-base (Jarvis & Higgs 1987).

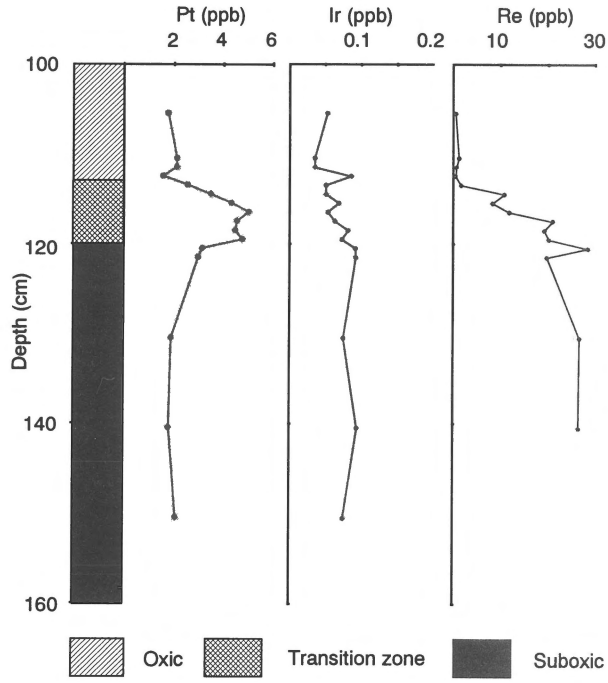

Fig. 3. Geochemical profiles of Pt, Ir and Re in a 330 ka old turbidite (data on a carbonate-free-base from Colodner et al. 1992). The oxic and sub-oxic sections of this turbidite are separated by a transition zone of intermediate colour from 113 to 120 cm.

less clear, but the peaks are indicative of significant post-depositional mobility (for details see Colodner et al. 1992). Mobility of iridium and other platinum-group elements has important implications for the interpretation of enrichments reported at extinction horizons such as the Cretaceous-Tertiary boundary.

Summary and outlook

Using examples from the Madeira Abyssal Plain, I have illustrated how concentration versus depth profiles in turbidites can be used to determine unequivocally if and how diagenetic processes affect the distribution of certain components. Using the instantaneous nature of turbidite emplacement and the extreme uniformity of the mud, it was illustrated that differentiation between organic matter of marine origin and organic matter of terrestrial origin can be heavily biased because of preferential preservation of non-reactive components. It became also apparent that various elements show significant post-depositional mobility; some of these (e.g. Ir, Pt) are frequently assumed to be immobile.

So far the emphasis was on organic carbon and redox-related diagenetic processes. The turbidite approach can, however, also be used to study other diagenetic processes. For instance, turbidite currents may transport carbonate-rich material in contact with undersaturated bottom water. On the basis of the time of emplacement and the degree of carbonate dissolution, it is then possible to determine the *in-situ* dissolution rate at a known degree of undersaturation (Wilson & Wallace 1990). The vertical homogeneity of the turbidite unit can also be used for the identification of post-emplacement signals of near-surface bioturbation. Although the mixed layer depths deduced from ^{210}Pb, ^{230}Th and foraminifera profiles were similar, the bioturbation intensities in terms of biodiffusion coefficients (D_B) were found to be different for each of the three tracers (Thomson et al. 1988). Tracer-dependent bioturbation intensities illustrate the complexity one may

encounter when studying bioturbated sedimentary sequences.

Finally, there are many more scientific problems which can be approached by using the unique characteristics of these turbidites. One could consider the oxidation of sulphide minerals or the formation of magnetic minerals by the downward propagating oxidation front, the dissolution of biogenic silica, and the determination of relative reactivities of molecular biomarkers, to mention a few.

References

Berner, R.A. 1980 Early diagenesis. A theoretical approach. Princeton Press, Princeton, NJ, 241pp

Buckley, D.E. & R.E. Cranston 1988 Early diagenesis in deep sea turbidites: The imprint of paleo-oxidation zones – Geochim. Cosmochim. Acta 52: 2925–2939

Colley, S. & J. Thomson 1985 Recurrent uranium relocations in distal turbidites emplaced in pelagic conditions – Geochim. Cosmochim. Acta 49: 2339–2348

Colley, S., J. Thomson, T.R.S. Wilson & N.C. Higgs 1984 Post-depositional migration of elements during diagenesis in brown clay and turbiditic sequences in the North East Atlantic – Geochim. Cosmochim. Acta 48: 1223–1235

Colley, S., J. Thomson & J. Toole 1989 Uranium relocations and derivation of quasi-isochrons for a turbidite/pelagic sequence in the Northeast Atlantic – Geochim. Cosmochim. Acta 53: 1223–1234

Colodner, D.C., E.A. Boyle, J.M. Edmond & J. Thomson 1992 Post-depositional mobility of platinum, iridium and rhenium in marine sediments – Nature 358: 402–404

De Lange, G.J. 1988 Geochemical and early diagenetic aspects of interbedded pelagic/turbiditic sediments in two North Atlantic Abyssal Plains. Ph.D. Thesis University of Utrecht, Geologica Ultraiectina 57, 189pp

De Lange, G.J. 1992 Distribution of exchangeable, fixed, organic and total nitrogen in interbedded turbiditic/pelagic sediments of the Madeira Abyssal Plain, Eastern North Atlantic – In: J.J. Middelburg & S. Nakashima: The geochemistry of North Atlantic Abyssal Plains. Mar. Geol. 109: 95–114

De Lange, G.J., I. Jarvis & A. Kuijpers 1987 Geochemical characteristics and provenance of late Quaternary sediments from the Madeira Abyssal Plain, North Atlantic – In: P.P.E. Weaver & J. Thomson (eds): Geology and Geochemistry of Abyssal Plains – Geol. Soc. Lond. Spec. Publ. 31: 147–165

Emerson, S. & J.I. Hedges 1988 Processes controlling the organic carbon content of open ocean sediments – Paleoceanography 3: 621–634

Jarvis, I. & N. Higgs 1987 Trace element mobility during early diagenesis in distal turbidites: Late Quaternary of the Madeira Abyssal Plain, North Atlantic – In: P.P.E. Weaver & J. Thomson (eds): Geology and Geochemistry of Abyssal Plains – Geol. Soc. Lond. Spec. Publ. 31: 179–213

Middelburg, J.J. 1992 Organic matter decomposition in the marine environment – In: W.A. Nierenberg (ed.): Encyclopedia of Earth System Science, Academic Press, San Diego: 493–499

Middelburg, J.J. & G.J. de Lange 1988 Geochemical characteristics as indicators of the provenance of Madeira Abyssal Plain sediments – Ocean. Acta 11: 159–166

Middelburg, J.J. & S. Nakashima 1992 The geochemistry of North Atlantic Abyssal Plains – Mar. Geol. 109: 1–194

McCave, I.N. & K.P.N. Jones 1988 Deposition of ungraded muds from high-density non-turbulent turbidity currents – Nature 333: 250–252

Pearce, T. & I. Jarvis, 1992 The composition and provenance of turbidite sands: Late Quaternary Madeira Abyssal Plain – In: J.J. Middelburg & S. Nakashima (eds): The geochemistry of North Atlantic Abyssal Plains, Mar. Geol. 109: 21–51

Prahl, F.G., G.J. de Lange, M. Lyle & M.A. Sparrow 1989 Post-depositional stability of long-chain alkenones under contrasting redox conditions – Nature 341: 434–437

Salomons, W. & U. Förstner 1984 Metals in the hydrocycle. Springer Verlag, Berlin, 349pp

Scholten, S.O. 1991 The distribution of nitrogen isotopes in sediments. Ph.D. Thesis University of Utrecht, Geologica Ultraiectina 81, 100pp

Schüttelhelm, R.T.E., G.A. Auffret et al. (eds) 1989 Geoscience investigations of two North Atlantic Abyssal Plains – the ESOPE International Expedition. Org. Econ. Coop. Dev. and Nucl. Energy Agency, Comm. Eur. Community Jt. Res. Cent., Luxembourg

Tegelaar, E.W., J.W. de Leeuw, S. Derenne & C. Largeau 1989 A reappraisal of kerogen formation – Geochim. Cosmochim. Acta 53: 3103–3106

Thomson, J., S. Colley, N.C. Higgs, D.J. Hydes, T.R.S. Wilson & J. Sørensen 1987 Geochemical oxidation front in North East Atlantic distal turbidites and their effect in the sedimentary records – In: P.P.E. Weaver & J. Thomson (eds): Geology and Geochemistry of Abyssal Plains – Geol. Soc. Lond. Spec. Publ. 31: 167–177

Thomson, J., S. Colley & P.P.E. Weaver 1988 Bioturbation into a recently emplaced deep-sea turbidite surface as revealed by $^{210}Pb_{excess}$, $^{230}Th_{excess}$ and planktonic foraminifera distributions – Earth Planet. Sci. Lett. 90: 157–173

Weaver, P.P.E. & A. Kuijpers 1983 Climatic control of turbidite deposition on the Madeira Abyssal Plain – Nature 306: 360–363

Weaver, P.P.E. & J. Thomson 1987 Geology and Geochemistry of Abyssal Plains – Geol. Soc. Lond. Spec. Publ. 31, 246pp

Weaver, P.P.E. & R.G. Rothwell 1987 Sedimentation on the Madeira Abyssal Plain over the last 300.000 years – In: P.P.E. Weaver & J. Thomson (eds): Geology and Geochemistry of Abyssal Plains – Geol. Soc. Lond. Spec. Publ. 31: 71–89

Wilson, T.R.S. & H.E. Wallace 1990 The rate of dissolution of calcium carbonate from the surface of deep-ocean turbidite sediments – Phil. Trans. R. Soc. Lond. A331: 41–49

Wilson, T.R.S., J. Thomson, S. Colley, D.J. Hydes, N.C. Higgs & J.

Sørensen 1985 Early organic diagenesis; the significance of progressive subsurface oxidation fronts in pelagic sediments – Geochim. Cosmochim. Acta 49: 811–822

Wilson, T.R.S., J. Thomson, D.J. Hydes, S. Colley, F. Culkin & J. Sørensen 1986 Oxidation fronts in pelagic sediments: Diagenetic formation of metal-rich layers – Science 232: 972–974, 234: 1129