Ocean circulation as mechanism and Pacific nutrients as fuel for OAE 2

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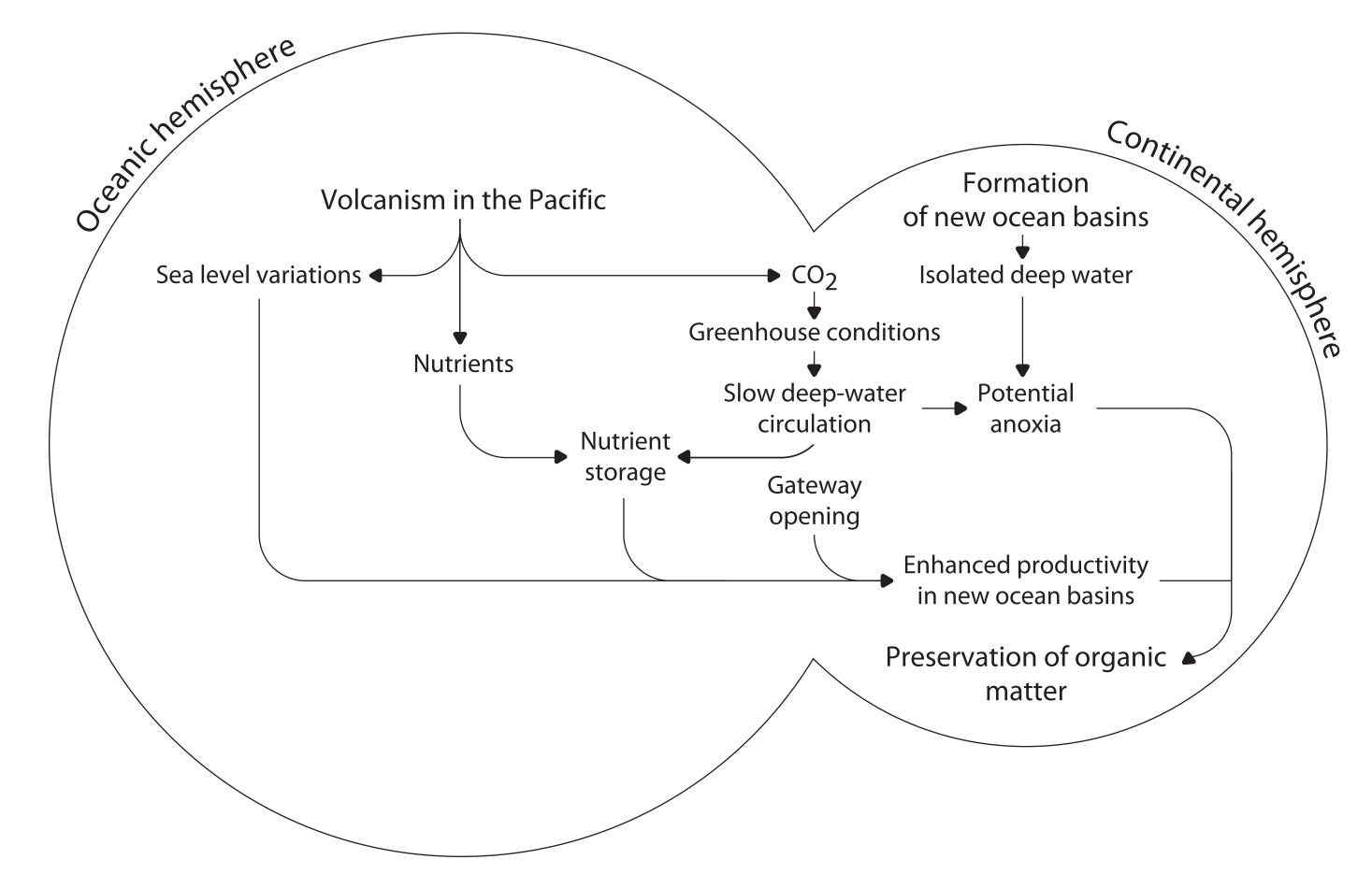


Figure 1 Graphical abstract (flux diagram showing the relation between forcing mechanisms, processes and products related to productivity-driven oceanic anoxic events). Note the much larger size of the 'oceanic hemisphere' compared to the 'continental hemisphere'. Comparison with Fig. 2 shows that preservation of organic matter was favoured in the newly formed ocean basins.

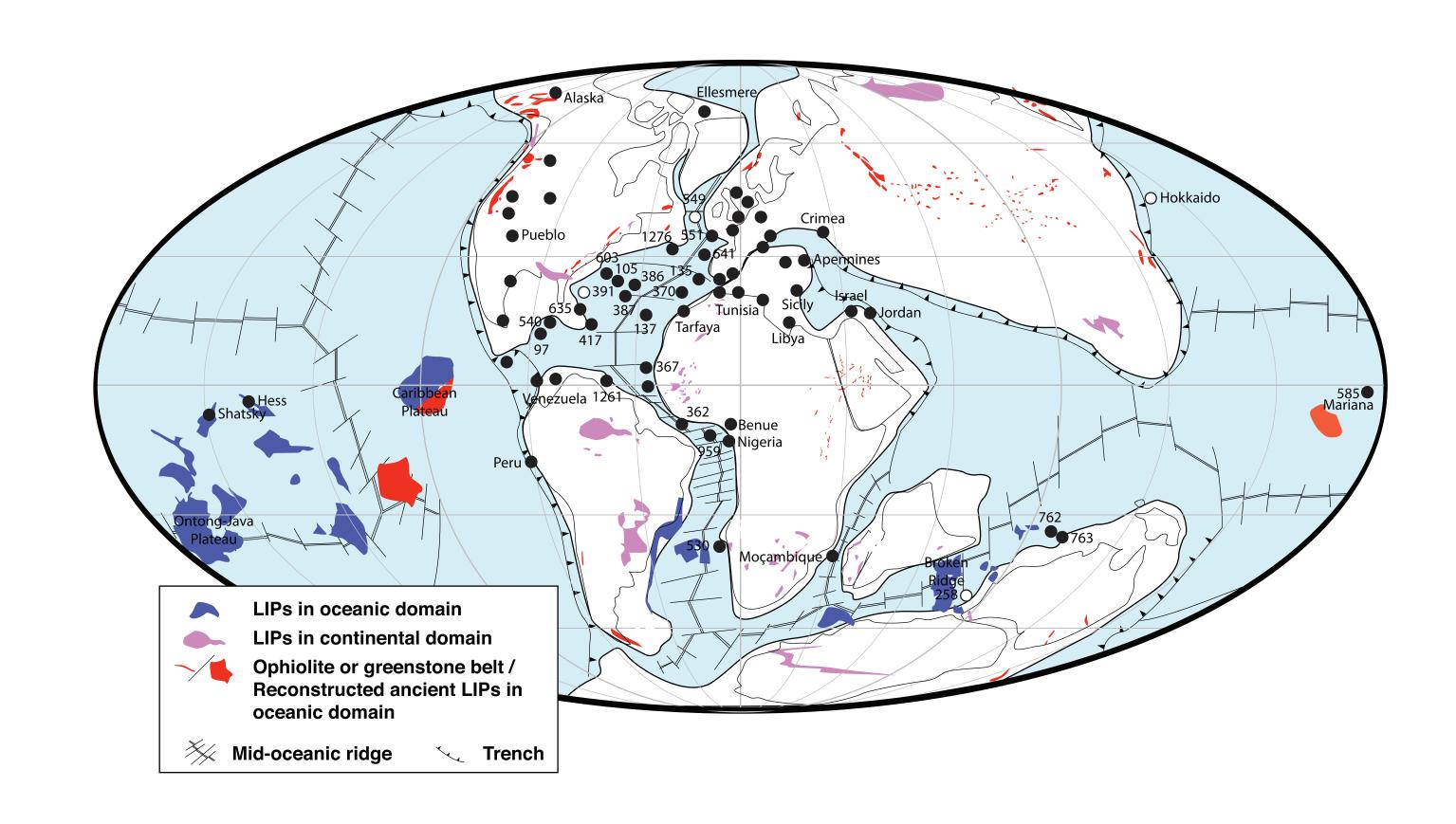


Figure 2 Reconstructed palaeogeographic map at ca. 90 Ma showing the location of Large Igneous Provinces (LIPs) and of known OAE 2-related deposits. Filled circles indicate dark-coloured, organic-rich sediments and open circles indicate organic-poor sediments. Numbers correspond to DSDP and ODP drilling sites. The distribution of continental masses is based on Scotese (2004) and the map with its LIP distribution is a modification based on Utsunomiya et al. (2007). Black shales compiled by Kuroda and Ohkouchi (2006) with alterations.

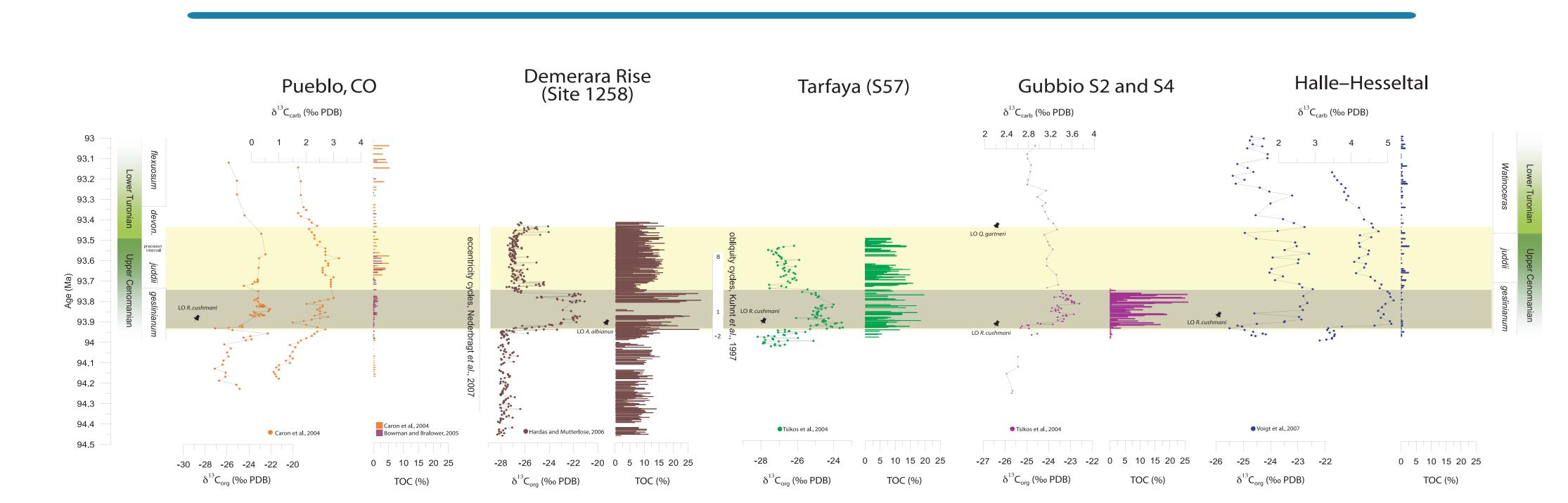
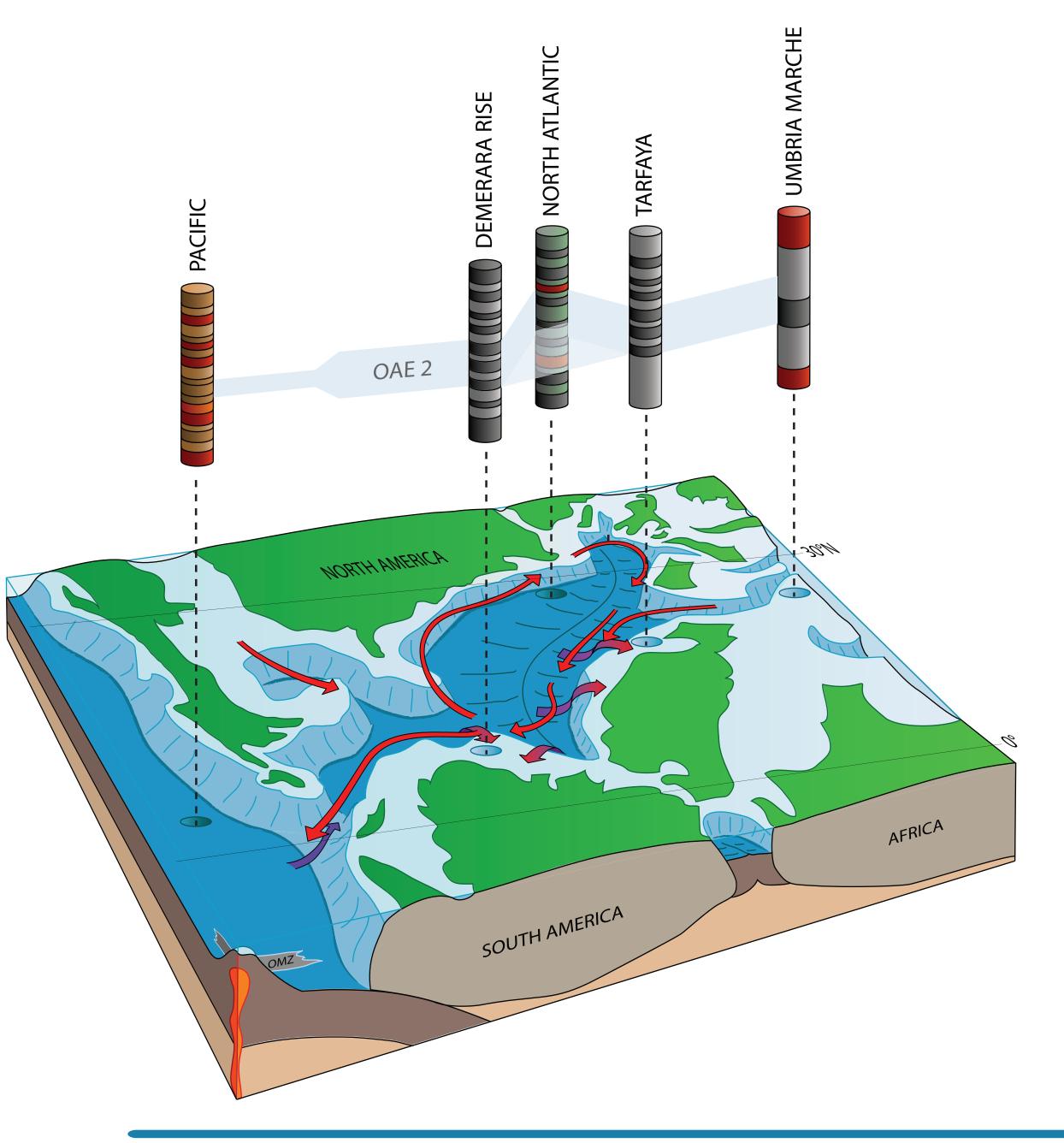


Figure 3 Transatlantic correlation of key Cenomanian/Turonian localities. Epicontinental sea sections (Pueblo, Halle-Hesseltal) have low total organic carbon (TOC) throughout. Open ocean sections show a west to east time lag in the onset of organic matter deposition. North Atlantic open ocean sections (Demerara and Tarfaya) also maintain these high TOC values throughout the OAE (yellow box) while Gubbio only has high TOC values during the Bonarelli Level (light grey box).

INTRODUCTION The hypothesis that large igneous events caused the environmental responses that ultimately led to oceanic anoxic events (OAEs) is plausible but not proven. One of the problems related to this hypothesis concerns the link between volcanic nutrient input into the marine realm and enhanced marine productivity (Fig. 1); oceanic plateaux roughly coeval with OAE 2, for instance, are located in the Pacific Ocean while OAE 2 is best developed in the North Atlantic Basin (Fig. 2). Here we develop on the ideas of previous authors and explore the hypothesis that volcanism in the Pacific provided the fuel for OAE 2 by leading to nutrient storage in the deep Pacific. Based on climate modelling (Figs. 6–8), we propose that changing ocean circulation provided the link between large igneous events and productivity-driven OAEs (Figs. 4, 5).



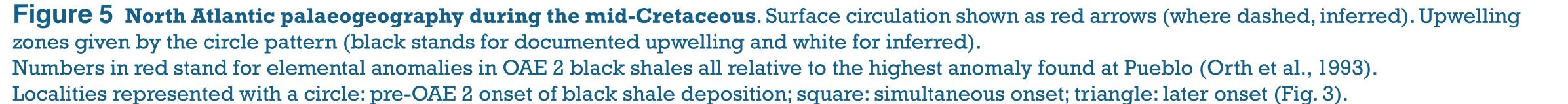
at the Cenomanian/Turonian boundary.
Surface circulation shown as red arrows.
Upwelling shown as purple/red arrows. Five key
OAE 2 localities are shown with a schematic representation of their sedimentary sequences.
In the deep Pacific, brown and red sediments
comprise the whole of the sedimentary sequence. Locally, on the flanks and tops of oceanic plateaux and within oxygen minimum

Figure 4 Deep sea sedimentation patterns

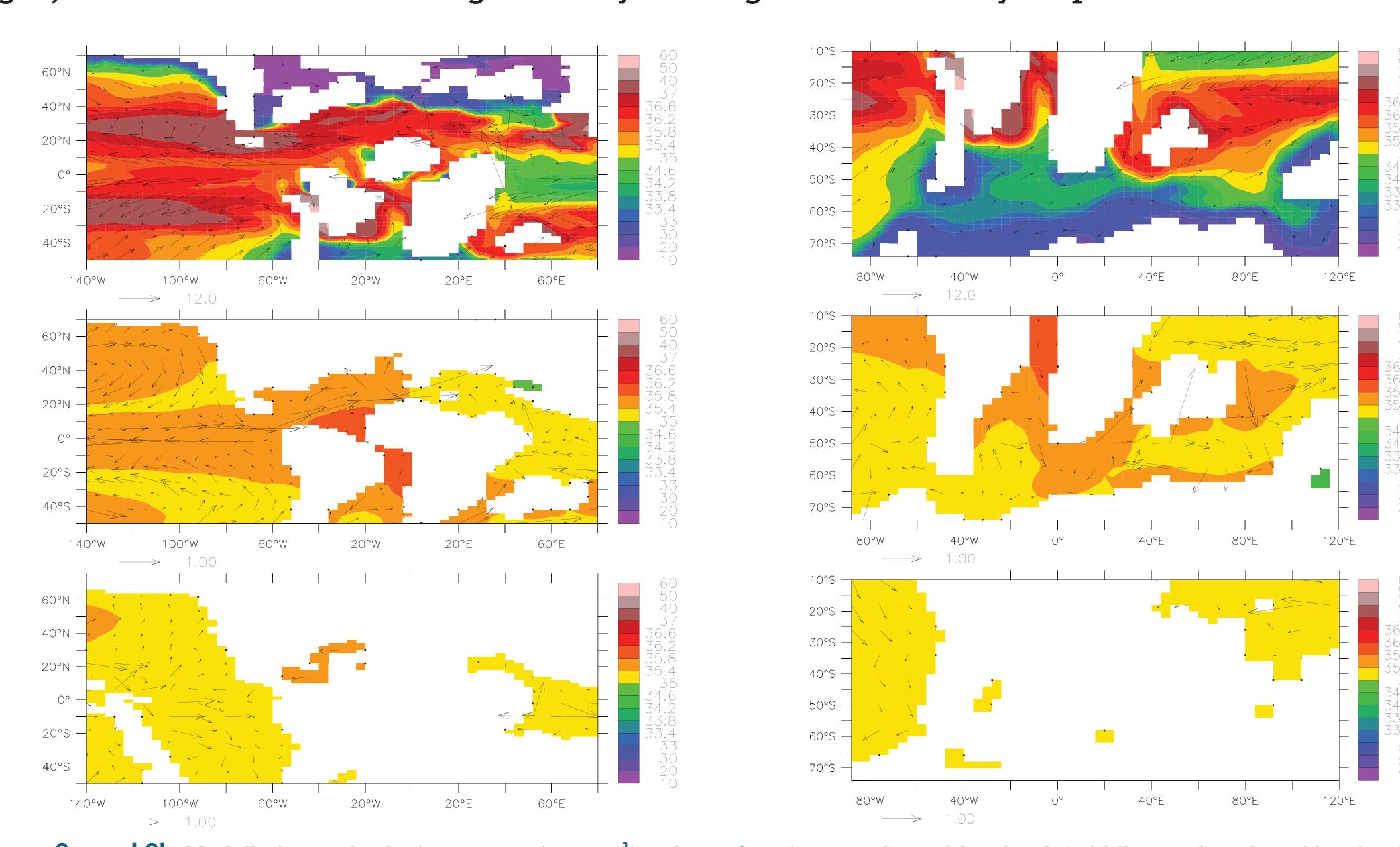
In the deep Pacific, brown and red sediments comprise the whole of the sedimentary sequence. Locally, on the flanks and tops of oceanic plateaux and within oxygen minimum zones (OMZs), black shales are found. These black shales are related to the passage of seamounts under the equatorial divergence zone. The bulk of OAE 2-related black shales are found in the equatorial North Atlantic. In the northern North Atlantic, black shales alternate with drab mudstones and have lower TOC. In the western Tethys, OAE 2 is represented by a single horizon, the Bonarelli Level. This map is a modification of Blakey's mid-Cretaceous map (105 Ma); for the original see

http://jan.ucc.nau.edu/~rcb7/105marect.jpg.

Black shales initially CONCLUSIONS formed in the SW North Atlantic and later in the northern North Atlantic and western Tethys (Figs. 3-5). Elemental anomalies show the same spatial pattern: highest anomalies are found in the western parts of the North Atlantic and decrease towards the east. Proxy data are consistent with introduction of nutrient-rich intermediate water from the Pacific (Fig. 6a), through the Central American Seaway, that upwelled along the southern margins of the basin (Fig. 7) before being transported towards the rest of the basin as surface water (Figs. 5, 6a). The main drivers of the OAE 2related carbon cycle perturbation were the North Atlantic deposits.



METHODS/RESULTS To investigate whether ocean circulation is the mechanism behind black shale deposition during OAE 2, a global coupled climate model (CCSM 3) was used and an equilibrium simulation performed for the Cenomanian/Turonian (~90 Ma). General circulation patterns (Figs. 6 a, b) were investigated, as well as the connectivity with surrounding basins and the character of the connection. Upwelling was simulated (Figs. 7, 8) in order to track where intermediate water was brought to the surface. Our results are consistent with geologic proxy data (Figs. 3–5) that show a west to east time lag in the onset of organic matter deposition for the North Atlantic. The southern basins (S. Atlantic and proto-Indian oceans) show a sluggish and poorly developed circulation. Black shales found in these basins are likely related to this potential anoxia (Fig. 1) and did not contribute significantly to the global carbon cycle perturbation.



Figures 6a and 6b Modelled annual velocity (vectors, in cm.s⁻¹) at the surface (top panel), at ~1 km depth (middle panel) and at ~4 km depth (bottom panel). The results are a 5-year average over model years 1496–1500. Colours denote salinity (in g/kg). Prescribed surface boundary conditions (e.g. topography and vegetation) are mainly based on Scotese (2001). See also Sewall et al. (2007) for a detailed description of boundary conditions. The pattern observed for the North Atlantic relative to the Pacific, with a connection via the Central American Seaway, is an estuarine circulation.

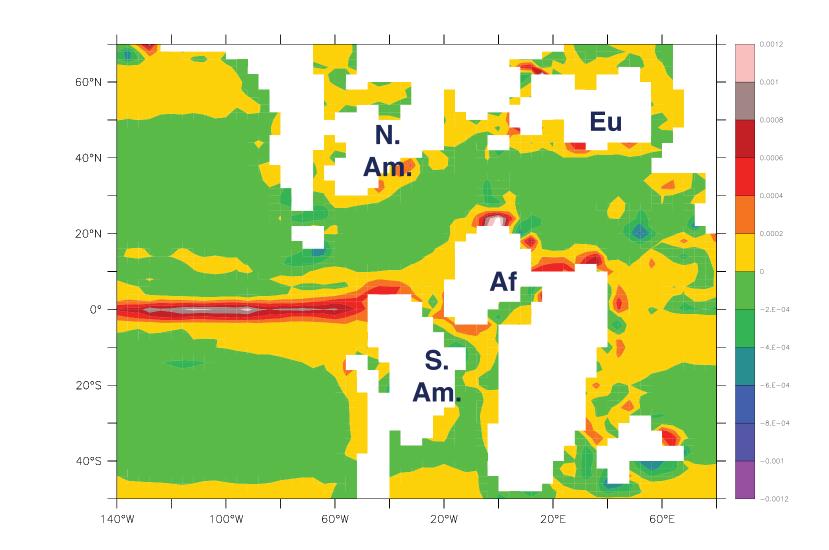


Figure 7 Modelled annual vertical velocity (in cm.s⁻¹) at 50 m depth. Positive velocities denote **upwelling** (red and vellow).

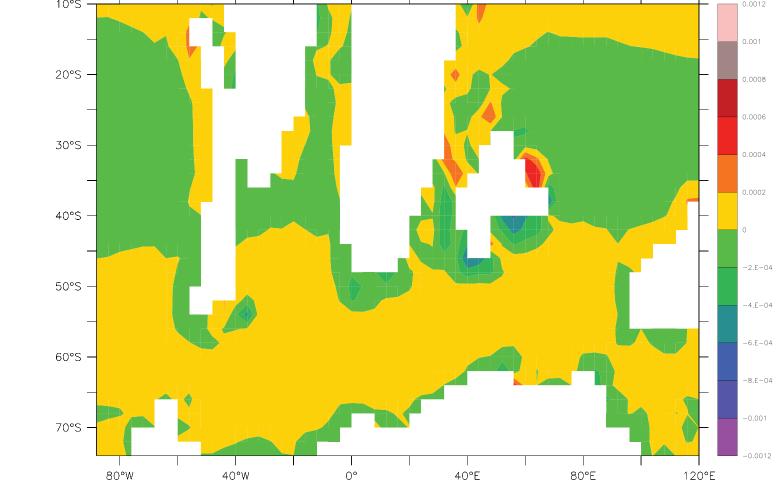


Figure 8 Modelled annual vertical velocity (in cm.s⁻¹) at 50 m depth in the Southern Ocean. Positive velocities denote **upwelling** (red and yellow).

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