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PELAGIC SEDIMENTS – PART 2

B. SILICEOUS SEDIMENTS

Siliceous remains in marine sediments come mostly from **diatoms**, single-celled plants ranging in size from a few to about 200 μm, and **radiolaria**, single-celled zooplankters which are typically 50 to 300 μm in size. Both are composed of hydrated amorphous silica (opal - $SiO_2 \cdot nH_2O$).

Silica (as orthosilicic acid, H_4SiO_4) is introduced to the oceans mostly via rivers (60% of the total flux, derived from rock weathering), with smaller contributions from hydrothermal fluids (20% of the total flux) and submarine weathering of sea-floor basalts (20%). The concentration of dissolved silica in the sea ranges from ~0 μmol L^{-1} (in nutrient-free surface waters) to about 200 μmol L^{-1} in deep North Pacific water. However, the solubility of opal is about 1100 μmol L^{-1}, which means that the ocean is everywhere undersaturated with respect to this phase. In contrast, $CaCO_3$ is only undersaturated below certain depths in the sea, as discussed in Part 1. Despite the considerable undersaturation, an estimated 1 to 10 % of opaline skeletons produced by biota in the upper ocean become permanently buried in the sediments. This is because the pore waters in the uppermost few millimetres of the sediment become enriched in dissolved silica as some skeletons dissolve, which inhibits further dissolution. Severe undersaturation can only be restored by exchange with the overlying bottom water. If the flux of opaline skeletons to the sea floor is high, as it is in areas of high productivity, then pore water silica concentrations may approach saturation. Under these conditions, the probability of skeletons surviving dissolution rises, and more are buried. Those diatom frustules and radiolarian skeletons that have a low surface area to volume ratio have the greatest probability of surviving dissolution (less surface area in contact with undersaturated water), as do those species that cover frustules with an organic coating.

There is no equivalent of a CCD for opal in the sea, and increased pressure causes only a minor increase in opal solubility. Therefore, unlike calcite, there is no topographic expression in the distribution map of opal in marine sediments; instead the distribution is very closely tied to primary productivity in the sea. Figure 1 (upper half) illustrates the rate of extraction of dissolved silicon by phytoplankton in global surface waters; this map essentially shows where nutrients well up to the surface to support primary production. Note the close correspondence with the opal concentration in the underlying sediments, shown in the lower half of Figure 1.

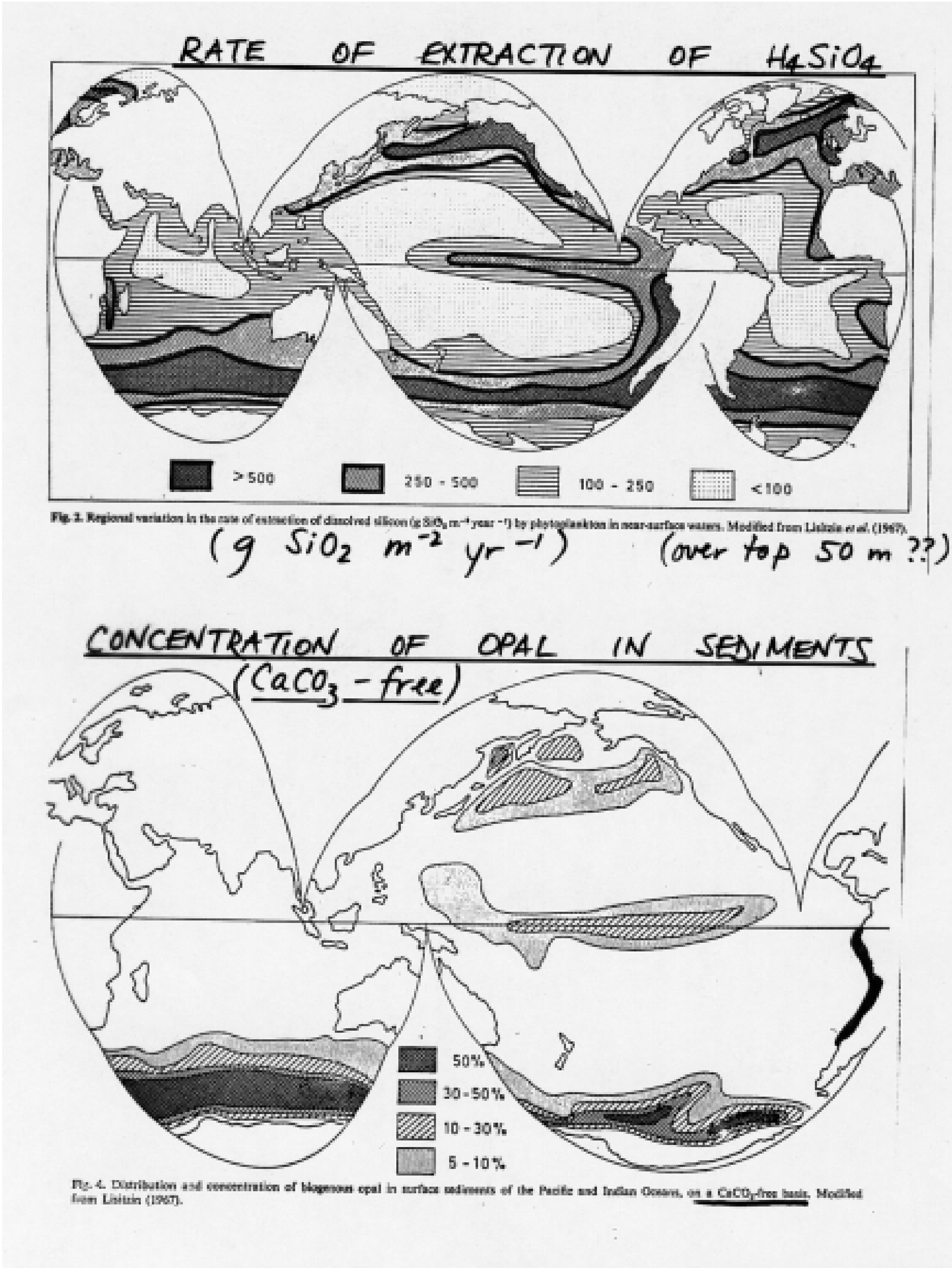

Figure 1. Upper panel: rate of extraction of dissolved silicon (as orthosilicic acid) by phytoplankton from the surface waters of the ocean (possibly the upper 50 m). Lower panel: concentration of opal (SiO2. NH2O) in surface sediments on the

seafloor. The data are presented on a carbonate-free basis (that is, the opal contents have been corrected for the diluting effect of $CaCO_3$ — this artificially increases the true concentration in bulk sediments). Note the close geographical correspondence between ***high*** rates of extraction and the opal content in the underlying deposits. After Lisitzin et al. (1967).

Siliceous deposits are found under the equatorial divergence in the Pacific, in the circum-Antarctic region, and in the North Pacific, all areas of upwelling. Not shown in the figure are the diatom oozes (>30% diatoms) that accumulate off the coasts of Peru and Namibia, both areas of profound coastal upwelling.

The very clear correspondence between sedimentary opal concentrations and upwelling regions is not seen in the $CaCO_3$ distribution (compare Fig. 2 in Part 1 with Fig. 1 above). This is because Si is a "hard part" nutrient and is in short supply in the surface ocean, unlike Ca^{2+} or CO_3^{2-}, which are the equivalent, but non-limiting, hard-part nutrients for calcium carbonate. The limiting "soft part" nutrients, nitrate and phosphate, are rapidly recycled in the upper waters of the ocean (only a fraction of N and P constantly escapes to the deep sea, mainly in fecal pellets) and can therefore gradually move away in near-surface waters from the point where they were welled up. Thus, they can continue to support the growth of organisms that make $CaCO_3$ skeletons some distance from upwelling regions. In contrast, each atom of Si that wells up is rapidly fixed into an opaline skeleton, which promptly sinks as the cells die or are grazed. Because $SiO_2 \cdot nH_2O$ dissolves more slowly than the cellular components degrade, Si is segregated from the soft part nutrients and consigned to deeper waters. It is this segregation that confines siliceous productivity to upwelling areas, while simultaneously allowing carbonate productivity to be more widespread.

The pattern in Figure1 has one somewhat anomalous feature: diatom frustules are very rare in sediments in the North Atlantic, even though diatom productivity is high in the area in the spring and summer. The explanation of this lies in a combination of oceanic circulation and the way in which dissolved silicate is used by plankton relative to phosphate. Phosphorus is a soft-part nutrient, unlike Si, which is fixed into the shells of plankton. Therefore, a larger proportion of P is regenerated at shallow depths in the ocean compared to Si. Since the North Atlantic is continually exporting deep water and importing surface waters, it exports proportionately more Si than P on average. This is reflected in the average Si:P ratio in the North Atlantic water column which is significantly lower than that in the Pacific. Water that wells up or is mixed into the euphotic zone in the North Atlantic is therefore slightly depleted in silica *relative to* phosphate. To maximize their growth given these conditions, diatoms conserve Si by making thinner walled shells. These are more susceptible to solution once the cell dies and it is this that accounts for the dearth of diatom opal in North Atlantic sediments -- the shells literally all dissolve before they get buried. In contrast, the abundance of silica compared to phospate in upwelling waters in the North Pacific fosters production of thick-walled frustules. It takes longer to dissolve these, and this allows a significant proportion to be buried in the sediments below the (usually shallow) depth where the sedimentary pore waters become saturated with dissolved silicate.