Upwelling influence on the Galician coast: silicate in shelf water and underlying surface sediments

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Abstract--Local characteristics in the upwelling of Galicia (NW Iberian Peninsula) are studied in terms of dissolved silicate patterns in the seawater column and opal distribution in the sediments. Freshwater input, upwelling, remineralization and sedimentation are considered. The freshwater silicate input is not important during the upwelling season. Upwelling is the main process controlling silicate biogeochemistry activity in the coastal zone. Areas of silicate remineralisation in the seawater column and opal abundance in surface sediment practically coincide. These together define the coastal limit of upwelling influence and its diverse local effects. Galician upwelling is important in the area surrounding three well-defined zones; Cape Finisterre, Cape Prior and La Coruña Canyon. South of Finisterre upwelling is more intense and closer to the coast. To the north, it is discontinuous and keeps distant from the coast, being near to the edge of the continental shelf.

1. INTRODUCTION

Upwellings are usually described in terms of hydrographical parameters as salinity and temperature. Nevertheless, the dynamics of silicate are particularly intense in these areas and silicate in seawater and opal in the sediment could be a useful tool for describing the meso-scale characteristics of Galician upwelling.

The input of silicate to the photic layer along with other nutrient salts implies the fertilization of surface water and typically results in a diatom bloom (Margalef, 1958). During upwelling, the use of dissolved silicate in the building of frustules, their sinking, remineralization and sedimentation involves a substantial increase in the activity of the biogeochemical processes in silicon. These processes may increase 4-10 times in relation to periods of upwelling relaxation (Prego et al., 1995).

Each upwelling region has its own characteristics with respect to silicate dynamics (Nelson et al., 1981). One region subjected to this phenomenon is the Galician coast (Northwestern Iberian Peninsula). Upwelling of North Atlantic Central Water (NACW), a water mass situated at 70-500 m depth, occurs off the coast of Galicia during the summer season (Fraga, 1981). To a large extent, latitudinal displacement of North Atlantic anticyclonic gyre plays a major role in seasonal upwelling intensification in the area (Wooster et al., 1976). At a minor scale, the incidence of winds (McClain et al., 1986) and the general circulation of NACW from the Azores or the Bay of Biscay (Rios et al., 1992) must be considered. Even more locally, upwelling is strongly influenced by topographic features of the coastline, intensifying in the surrounding Finisterre Cape (Blanton et al., 1984).

The sediments affected by upwelling phenomena show particular features which differentiate them from areas with a different hydrodynamic regime (Diester-Haass, 1978; Thiede and Suess, 1983), and thus provide an idea of the average structure of an upwelling zone (Margalef, 1978). The Galician upwelling system has an effect on shelf sedimentary processes, as shown by the distribution of muds in surface sediments (Rey and Diaz del Rio, 1987; Rey, 1990; Lopez-Jamar et al., 1992). Analyses of the fossil diatoms in the shelf sediments of the Galician upwelling have only been considered very recently (Bao et al., 1993). The same is true of dissolved silicate in the seawater column, which has neither been dealt with in the studies on nutrient salts off the Galician coast nor even been considered in the simple hydrographical descriptions (Prego, 1990).

With regard to Galician upwelling, two important issues have still not been considered in studies to date: (1) a meso-scale description, since only a general view of Finisterre upwelling has been made, and (2) silicate has not been used as a source of information in this seasonal phenomenon. The local characteristics of Galician upwelling are studied here for the first time. They are described using dissolved silicate annual patterns in the water column together with the opal distribution in the sediments where the yearly upwelling background remains.

2. STUDY AREA AND METHODS

The Galician coastline is 1720 km in length and lies in the northwest corner of the Iberian Peninsula (Fig. 1). The continental shelf of Galicia is relatively narrow. The 200 m depth isobath lies at 15-30 km from the land. The rugged coastline is penetrated by a series of rias (flooded tectonic valleys) which receive river contributions at their heads. The granitic nature of the Galician ground influences the concentration of silicate in the fluvial waters in such a way that the freshwaters entering the rias have a concentration between 60 and 160 µM Si. The river's silicate contribution is 8.1 mol s^{-1} in summer, being slightly greater of the south of Finisterre Cape (Table 1).

The samples and data (Manriquez et al., 1978; Mouriño et al., 1985) used in this paper correspond to the Galicia IV and VIII cruises on board the R.V. Cornide de Saavedra and Garcia del Cid in 1977 and 1984, and to the Breogan 984, 485, 486 and 387 cruises on board the R.V. Cornide de Saavedra between 1984 and 1987.

For the coastal seawater study, samples were taken from Galicia cruises at various depths in Niskin bottles. The dissolved silicate was determined using autoanalytical procedures (Technicon AAII), immediately following the sampling, according to the method described by Strickland and Parsons (1968) and Hansen and Grasshoff (1983). Precision was in the order of ±0.04 µmol kg^{-1}.

For the opal study, sediment samples from the Breogan cruises were selected. Biogenic opal in the sediments was extracted following the rapid wet alkaline solution procedure described in Mortlock and Froelich (1989). Silica was extracted into a 2M Na_2CO_3 solution at 85°C for 5 h. The resulting extract was measured for the dissolved silicate concentration according to Strickland and Parsons (1968).

3. RESULTS AND DISCUSION

Non-remineralized dissolved silicate is introduced to the Galician coastal zone by river freshwater and offshore seawater. If the fluvial silicate flux is unimportant in relation to that from upwelled seawater, it is possible to use the silicate as an upwelling tracer.

3.1. Freshwater influence

The rivers of Galicia do not lead out directly into the ocean, but rather into the rias (Fig. 1). Here, a river-ria-ocean interchange takes place (Prego and Fraga, 1992). The freshwater input of silicate to the coastal water is high during the rainy season (near to 90 mol s^{-1}), but this nutrient is scarcely used by the diatoms (Prego and Fraga, 1991). On the contrary, during the summer season, silicate contributions from the rivers are very low. So, the ria of Vigo only receives 2% of silicate from freshwater during upwelling events (Prego et al., 1995). Nevertheless, it is possible to estimate dissolved silicate flux in rivers to evaluate its importance. So, based on flow data and silicate concentration, 18 Galician rivers (Fig. 1) contributed to all the various rias 8.1 ± 3.7 mol s^{-1} (Table 1). It is a very low flux for two reasons: (1) the ria of Vigo alone receives 6.5 mol s^{-1} from the ocean during upwelling events, that is, an input similar to the freshwater silicate outflow for all the Galician coast; and (2) a flux of 11.8 mol s^{-1} is equivalent to 1.24×10^{11} mgC day^{-1} [the Galician continental shelf has an area of 6.4 x 10^9 m^2 and the C:Si relationship is near to 10:1, Prego et al. (1995)]. The freshwater input could therefore only justify a primary production of 20 mg C m^{-2} day^{-1}. On the Galician coast during the upwelling season the primary production is 30-40 times greater.

The freshwater silicate must be consumed for building diatom frustules in the innermost parts of the rias. The frustule exportation caused by ria circulation is not important during winter, as is shown by the low percentage abundances of freshwater diatoms found in the rias adjacent to the shelf (Bao et al., in press). Despite this, the distribution of opal constituents on the Galician continental shelf is not wholly irrelevant to the ria contributions. Water circulation in the rias exports diatoms to the adjoining continental shelf (Estrada, 1984), although it is not caused by the river flow but rather by upwelling (Prego and Fraga, 1992).

Consequently, the freshwater influence on the Galician shelf is very low and upwelling will exert the main effect on the silicon biogeoehemistry during the upwelling season.

3.2. Upwelling influence

The silicate transported by the incoming subsurface water constitutes an important source of dissolved silicate on the Galician coast. In spring and summer, the meteorological conditions are favourable for marine upwelling (Fraga, 1981). The subsurface seawater, rich in nutrient salts, is upwelled near to the Finisterre Cape area (Fig. 2, TS section 4: the dense grouping together of points, compared with other TS sections, indicates the presence of the main upwelling zone off the Galician coast) where Fraga et al. (1982) found a quasi-permanent upwelling during summer. The concentration of dissolved silicate is maximum near to the cape, with 3 µM Si at a depth of 20 m, decreasing rapidly offshore (Fig. 3, lower right box).

The subsurface seawater differs between north and south of Finisterre. A temperature salinity (TS) diagram shows these latitudinal differences during an upwelling event. The Eastern North Atlantic Central Water lies south of Finisterre (TS shape >, sections 1, 2 and 3 in Fig. 2), as defined by Fiuza (1984), and similar water is also found north, although here it is modified by surface mixing (TS shape e, sections 5,6 and 7 in Fig. 2), as previously described Fraga et al. (1982). Nevertheless, the differences in silicate in both areas to the north and south of Finisterre have not been considered until now. The silicate temperature (Si-T) diagram in Fig. 2 shows how the silicate concentration is lower (less than 4 µM, sections 5, 6 and 7 in Fig. 2) and the layer of depletion is greater in the northern zone (a high number of points are on the zero µM line, sections 5-7 contrary to sections 1-4; Fig. 2), i.e. the formation of diatom frustules and, thus, their presence in the sediment, must be less in this zone and greater on the shelf lying south of Finisterre, as confirmed in the sediment section.

The zone most influenced by upwelling, and the only one considered to date (Fraga, 1981; Blanton et al., 1984; McClain et al., 1986; Tenore et al., 1982), corresponds to the Finisterre Cape area. In the south of this area, upwelling extends along the continental shelf in front of the rias (1 µM Si, Fig. 3, lower right box), penetrating as far as the rias inner part (Prego, 1990). Nevertheless, upwelling is also present in the areas near Cape Prior (Fig. 1). In this area, it is less intense, silicate having a concentration of 1 µM at a depth of 20 m (Fig. 3, lower right box).

3.3. Remineralization influence

One of the effects of the high biological activity occurring in coastal upwellings is the presence of a marked remineralization (Whitledge, 1981) of organic matter near the continental shelf bottom. This subsurface increase in nutrient salts concentration (Codispoti, 1981) also occurs in Galician upwelling. In this area, outside the rias, an increase in nitrate concentration has been observed (Fraga, 1981; Blanton et al., 1984). The flux and budget of nitrogen (Prego, 1994) and oxygen (Prego, 1993) were calculated for the ria of Vigo including one upwelling event. Organic nitrogen remineralization within the ria accounted for 35%, and outside the ria, for 27% of the total contribution of inorganic nitrogen into this ria, 50 mol 0_2 s^{-1} being consumed in remineralization. Biogenic silicon is not detached from this process (Prego and Fraga, 1991; Prego et al., 1995); however, dissolved silicate has not, to date, been considered in the Galician upwelling. An example of this phenomenon is the situation in October 1977 whose maximum silicate concentration areas are described in Fig. 3. There is an increase in the silicate of the seawater column (up to 9 µM, Fig. 3) in relation to the 3-4 µM Si of seawater found at the continental edge (Fig. 2) or the upwelled water off Finisterre Cape (Fig. 2, section 4) which, according to Fraga et al. (1985) must be near to 3.5 µM Si. For this reason, the maximum levels of silicate must correspond to the area with the maximum remineralisation which, furthermore, shows the lowest levels of oxygen (Fig. 3). Both parameters for the water column present an inversely proportional relationship (Fig. 4):

July 1984: $[H_4SiO_4] = 22.4 - 0.0849\ [O_2]$ r = 0.88

October 1977: $[H_4SiO_4] = 20.6 - 0.0812\ [O_2]$ r = 0.96.

They have similar regression coefficients in two different years which correspond to the start and close of summer. Nevertheless, at the end of the upwelling season, silicate concentration is greater while oxygen is less (11 and 140 µM, respectively, Fig. 4).

Considering the remineralization of silicate as a result of Galician upwelling events, on this coast, remineralization is greater in the south zone. The northern area, as occurred with upwelling, is also now put at a disadvantage as regards the remineralization of silicate. Only 6 µM is attained in an area which, in comparison to the southern area, is relatively small, where practically the whole of the shelf area has this concentration. It is here where even higher values occur. In front of the Rias of Muros and Arosa lies a strip with the highest values, over 9 µM (Fig. 3). So, silicate remineralization marks the limits of the influence of upwelling and locally highlights its varying importance off the Galician coast (Fig. 3). Generally, upwelling is more intense near to and south of Finisterre Cape and is less intense and continuous to the north. The Finisterre area is the most outstanding, although the Prior Cape area must also be considered, which confirms the importance previously noted of upwelling near this area. High remineralization exists in an area between these two capes (Fig. 3), and this is explained in the section dealing with sedimentation. The minimum of oxygen makes it possible to mark out the influence of upwelling on the Galician coast. At Finisterre and to the south, it lies near to the coast, broadly following the 100 m isobath. To the north, it keeps distant from the coast, being near to the edge of the continental shelf.

3.4. Influence on the sediments

The opal content of surface sediments shows highest concentrations where upwelling is strong and there is high biological productivity (Leinen et al., 1986). On the Galician coast, since fluvial influence is scarce, opal percent abundances in the surface sediment ought to bear a close relationship to the coastal activity produced by upwelling, i.e. the rise of subsurface seawater and remineralization.

In the sediment (Fig. 5) the highest percentages of opal are found to the south and in the proximity of Finisterre, slightly increasing from the edge of the continental shelf to the coast. To the north of the said cape, the opposite occurs, opal percentage increasing towards the 200 m isobath (Fig. 5).

Opal content in the sediment bears a close relationship to remineralization processes, which is illustrated by the two maps in Figs 3 and 5. On the continental shelf, the plot of percent opal in the sediments vs the highest dissolved silicate concentration in the water column (Fig. 6) is in accordance with the following expression:

$Opal = 0.45 + 0.142\,[H_4SiO_4]\quad r = 0.78.$

Thus, areas of remineralization in the seawater column and sedimentation are almost the same, even when considering different years, which points towards a constancy in these areas and upwelling effects on the Galician coast. If the photosynthesized organic matter is considered, indicated by particulate organic carbon (POC) (Fig. 5, lower right corner), upwelling exerts an influence on production, remineralization and sedimentation in areas near to and, more especially, situated on the continental shelf off Galicia. However, there is no strict relationship between the areas where organic carbon is synthetized and those where silicate reaches maximum values in the sediments. The absence of a direct spatial link between production and remineralization-sedimentation may be due to a kind of lateral shifting which differentiates between areas of production and areas of sedimentation, as it occurs in the rias (Prego, 1993).

An example of this on the Galician shelf is the maximum remineralization in the wedge shape formed by sedimentation in front of the rias to the south of Finisterre (Figs 3 and 5). Two factors influence the distribution of opal in sediment and silicate by remineralization. Besides the offshore ria pattern of upwelling at Finisterre is the increase of the residual circulation due to upwelling into these rias. The outgoing residual flow from the ria can be up to three times above that caused by river contribution (Prego and Fraga, 1992). This causes not only the phytoplankton and organic matter to be transported offshore of these rias (Estrada, 1984; Varela, 1990; Lopez-Jamar et al., 1992), but also an increase in the remineralization and opal content of the sediments in the rias adjacent to the shelf.

The elliptical area of high opal sedimentation and silicate remineralization situated between Cape Prior and Finisterre (Figs 3 and 5) will correspond to the upwelling occurring near the continental border, where the influence of a rapid decrease of the bathymetry due to the Canyon of La Coruña (Fig. 1) would aid the upwelling in this area. So, the most northerly zone with a high POC concentration (Fig. 5, lower right corner) may be the result of vertical seawater advection in this area.

4. CONCLUSIONS

Silicate and opal are very useful tools for recharacterizing upwelling more precisely in coastal areas such as Galicia. The silicon presence in the sediment and the water column give detailed information complementary to the classical parameters such as salinity, temperature or oxygen.

The fluvial influence on the contribution of silicate to the Galician coast is very low during the upwelling season (April-September). So, the upwelling is the main process that controls silicate biogeochemistry in the seawater column which is reflected in remineralisation and in the sediment.

The upwelling phenomenon in Galicia has highly influential local areas which, to date, have not been described in detail. In these areas, upwelling around Finisterre Cape may be more intense and persistent, in accordance with data on sediment and the seawater, but the upwelling near Prior Cape and La Coruña Canyon must also be considered.

Finally, according to the silica distribution in surface sediment as an historical record, the upwelling patterns in Galician coastal waters must repeat themselves year after year. Sediment and seawater column results together show that on the western Galician coast upwelling practically reaches the coastline, penetrating the Rias Bajas inland; conversely, off the northwest coast, it keeps at a distance occurring near the edge of the continental shelf.

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Fig. 1. Location of the study area in the northwestern Iberian Peninsula. River names are in capital letters.

Fig. 2. Temperature-salinity (TS) and silicate-temperature (SIT) diagrams in seven different sections across the Galician coastal zone during an upwelling event (data obtained from Mouriño et al., 1985). TS sections 1, 2 and 3 correspond to suptropical ENAW from the Atlantic Ocean; sections 5, 6 and 7 correspond to subpolar ENAW from the Cantabrian Sea; section 4 is where the upwelling influence is maximum, occurring, as expected, off Cape Finisterre. In the Si-T diagram, it is possible to observe the higher silicate concentration towards the south of Finisterre and the numerous points where the silicate concentration is zero towards the north of Finisterre.

Fig. 3. Silicate remineralization in the seawater column. Sampling stations are marked as circles. Isopletes are drawn following the maximum of dissolved silicate in the shelf samples. Off the shelf, 200 m depth values were used. Dashed line indicates oxygen minimum (data obtained from Manriquez et al., 1978). Right corner: dissolved silicate concentration at 20 m depth during an upwelling event (data obtained from Mouriño et al., 1985).

Fig. 4. Plot of dissolved silicate vs dissolved oxygen in the seawater column of Galician shelf in the beginning and at the end of summer upwelling. Upper 10 m depth values and those where silicate concentration was less than 0.2 µM have been rejected (data obtained from Manriquez et al., 1978; Mouriño et al., 1985).

Fig. 5. Percent opal distribution in surface sediments of the continental shelf. Dots indicate sampling stations, Right corner: integrated 0-30 m particulate organic carbon just after the upwelling season (data obtained from Mouriño et al., 1985).

Fig. 6. Plot of percent opal content in the sediments vs maximum dissolved silicate concentration in the shelf seawater column. This highest silicate is caused by remineralization in the aphotic zone. Values of nearest sediment samples in Fig. 5 to seawater column stations in Fig. 3 were selected

Table 1. Dissolved silicate inputs from rivers flowing into Galician rias during the upwelling season (April-September)

	Average flow (m^3 s^{-1})	Silicate concentration (µM)	Silicate flux (mol s^{-1})
Rias Altas (12 rivers)	27	144	3.9 ± 2.4
Rias Bajas (six rivers)	28	151	4.2 ± 2.8
All Rias	55	147	8.1 ± 3.7

Average estimations elaborated from Rio and Rodriguez (1992), Antelo (1992) and Comisaria de Aguas del Norte de España data. The rias to the south of Finisterre Cape are known as the Rias Bajas and those to the north, Rias Atlas.