Gene told me about. About the work of Walter Maunder 100 years before, when he had thought that there was a prolonged period of time in the 1600s when the Sun wasn't so active.

That really piqued my curiosity, and I began digging into it. The trail was, initially, purely historical, initiated by Gene Parker telling me about Maunder, and driven by my prejudice of trying to find examples from the past that would disprove, once and for all, the notion of strong Sun-weather relations. A devout negativism on this subject was the gospel at the High Altitude Observatory anyway and the catechism that I had been taught and had taught to others. And although I was indeed an acolyte, I was trying to examine the early origins of Sun-weather claims, like unrolling and deciphering the Dead Sea Scrolls of solar physics. But it was mostly a love of history that took me down the trail.

Weart: I see. So just along with your other stuff, from time to time you would go and try and dig something up.

Eddy: I did it all on the side, quite on my own, and sneaked it in here and there. For something had jolted my professional life, which was probably the worst and maybe also the best thing that had ever happened to me. That was in 1973. I had been at the High Altitude Observatory for almost ten years at that time. Mostly teaching courses, and doing these eclectic forays into this and that. Nothing very profitably. There came along a major cutback in the funding for our parent organization, the National Center for Atmospheric Research, NCAR. They had to lay off a number of people. I was one of those selected to be let go. Then some of my friends at NASA thought that I'd had shown some promise as a writer. They offered me a temporary job, because I had worked as a PI on a Satellite Coronagraph in the 1960s, writing a book for NASA as part of the series on the Skylab spacecraft. So I got a job to write this book, in Colorado, that kept income coming in. It also enabled me to continue work on the Maunder Minimum although not openly. It was a job that I had to stretch out as long as I could, until I could get a [permanent] job. It became for me, intentionally or unintentionally a kind of Scheherezade exercise, to be prolonged as long as possible. Which I did. But it enabled me to do a bunch of traveling, mostly to Harvard, where two of the solar instruments on the Skylab were built, and where there were excellent historical libraries. And to Washington, where I could use the Naval Observatory Library.

Weart: One of the world's great libraries for this stuff.

Eddy: In connection with my visits with investigators on these satellite instruments, I would go and spend time in the libraries that were far better than those in Boulder. In this way, I was able to read and collect original texts—mostly in Latin—from the time of the Maunder Minimum. And collect old pictures and original data on both sunspots and aurorae, and naked-eye observations from the Orient.

Weart: At this point, you were beginning to believe that the Maunder Minimum was real.

Eddy: I was beginning to change my mind and to believe it was real, based on the original documents I read, and as a result of immersing myself in the time, as happens when you dig into history. But it was a shock to me to suspect that my original feelings and biases were wrong.

Weart: And at this point, the evidence was still mainly sunspots. You hadn't gotten into the aurora or the carbon-14 yet?

Eddy: It was entirely sunspots at first. I wanted to check these original records, so I did that as much as I could, and the NASA editorial job enabled me to do that. Then, when that came together, I began to look around for other ways that there might be for checking on it—that Maunder and Sporer didn't have. I knew I would face an uphill battle convincing my colleagues about the reality of the Maunder Minimum, if it leaned entirely on accounts from so long ago. Why should you trust someone in the 1600s when we are so much smarter and know so much more now? As scientists, we're trained to discount what one finds in old books, I think. You know science does, of necessity, have to look at things through a rather narrow window of time, because most of what earlier generations believed has been replaced by something else. Some things may be of interest for historical reasons, like whether Galileo was left-handed, or Niels Bohr thought this or that, but usually not for practical or applied ones. And I thought there ought to be some way to check on what Maunder, and earlier, Sporer, had claimed.

Because I had been trained in astro-geophysics and knew something of the other ways that the Sun affects the Earth, I looked hard at historical records of aurorae. Because of my interest in history, I looked very hard at Oriental naked eye sunspot [observations] in the hundreds of years before the Maunder Minimum and after, because they were continued after the advent of the telescope. I pushed it as hard as I could. And once when I was telling Gordon Newkirk about my early findings, he said, "You know, you really ought to look at carbon-14." That answers the question you raised earlier.

Eddy: No. Not before Gordon's suggestion, which was extremely valuable. I taught myself about cosmogenic nuclides and all of that. And tree rings, and bristle-cone pines. And I got acquainted with the Laboratory of Tree Ring Research in Tucson [Arizona].

Past Deep-ocean Circulation and the Paleoclimate Record-Gulf of Cadiz

PAGES 481,487–488

Deep marine currents are strongly influenced by climatic changes. They also deposit, rework, and sort sediment, and can generate kilometer-scale sedimentary bodies (drifts). These drifts are made of thoroughly bioturbated, stacked sedimentary sequences called contourites [*Gonthier et al.*, 1984]. As a consequence, change in the direction or intensity of currents can be recorded in the sediments.

The Gulf of Cadiz represents the pathway of a strong, warm (13°C) and saline (> 37 g l^{-1}) current called the Mediterranean Outflow Water (MOW), which comes out of the Mediterranean and spreads in the mid-depth North Atlantic at water depths of 800–1200 m. Its velocity is > 3 m s^{-1} when it flows out of the Strait of Gibraltar (Figure 1). A current named the Atlantic Inflow [*Nelson et al.*, 1999] flows back from the Atlantic into the Mediterranean. The MOW velocity quickly drops from the Strait of Gibraltar, but still reaches 0.2 m s^{-1} at Cape St. Vincent (southwest Portugal).

New, high-resolution bathymetry data presented in Figure 2 were collected during the CADISAR cruise on the R.V. *Le Suroît* (August 2001) using a multi-beam echosounder EM 300. The map covers an area ranging between N35° 35′ and N36° 35′ and W6° 40′ and W8° 10′ (Figures 1 and 2). It shows in detail the complex current activity in this area. Long Calypso piston cores were collected during the IMAGES V cruise with the French research vessel *Marion Dufresne* (September 1999). They allow reconstruction of the past MOW circulation, which was strongly influenced by paleoclimatic changes. This circulation affected the deep-water circulation on a global scale.

Present-day Circulation, Sea Floor Morphology

The new bathymetry and imagery data show that the MOW controls regional sedimentation patterns and explains the general way the Gulf of Cadiz sedimentary system works (Figure 2). When entering the Gulf, a part of the MOW is quickly deflected under the effect of the coriolis force and takes a northwest path [*Madelain, 1970*]. MOW captures particles supplied by Spanish rivers and from the shelf [*Grousset et al.*, 1988]. The particles are entrained and dispersed by the high energetic MOW on the continental slope in the Gulf of Cadiz and to the north beyond. The sedimentary features observed downflow from Gibraltar mirror the progressive decrease of MOW energy [*Kenyon and Belderson*, 1973]. Global grain-size of surface sediment also decreases when MOW velocity and competency (i.e. the ability of the flow to transport detritus in term of particle size) decrease.

Following the MOW westward from the Strait of Gibraltar, gravel lags and giant erosional features (GF in Figure 2) are first observed, and then, sand patches (SP in Figure 2), and sediment waves (SW in Figure 2) with their sand content decreasing westward [*Mélières*, 1974; *Kenyon and Belderson*, 1973; *Nelson et al.*, 1999]. A part of the MOW is channeled by the major, northern, intermediate or southern channels (MC, NC, IC, and SC, respectively, in Figure 2) or by secondary channels (SeC in Figure 2), such as the Gil Eanes channel (GE in Figure 2).

One of these channels follows a tectonic lineament oriented N45° that is associated with topographic highs and lows (DL in Figure 2). Some of the highs are circular and interpreted as diapirs of Triassic evaporites [*Mougenot*, 1988]. Others are escarpments with a more linear trend and represent probably submarine scarps of outcropping rocks or consolidated sediments. Most of topographic lows also have a circular shape. They are interpreted as collapse zones due to dissolution of Triassic evaporites. These observations suggest that the orientation of the south MOW channel, and hence, the flow direction, is locally controlled by tectonic features.

Recent tectonic stress is also documented by the presence of a mud volcano (MV in Figure 2) in the southeastern-most part of the map. On the landward side of the channels, MOW velocity decreases and fine particles deposit, forming thick sediment accumulations such as the Faro (FD in Figure 1) and the Guadalquivir drifts (GD in Figures 1 and 2; *Gonthier et al.*, 1984; *Mougenot*, 1988). They began to grow just after the Messinian (6–5.3 Ma), when the current Mediterranean-Atlantic connection formed [*Faugères et al.*, 1985a].

Another part of the MOW spills over a topographic high (TH in Figure 2) and strongly decelerates, and deposits particles forming extended fields of sediment waves in the depth interval between 1000 and 1500 m (Figures 1 and 2). This process induces very high sedimentation rates of up to 39 cm ka^{-1} in core MD99–2339 (J. Schönfeld, unpublished data, 2001). These high sedimentation rates and the continuous east-west shearing of surface sediment by MOW induces sediment deformation and failures (SF in Figure 2), with occasional rounded morphology, indicating simple sediment collapse without transport, shallow slumps, or bottleneck sediment flows, according to the terminology of *Prior and Coleman* [1979]. Frequent earthquakes—such as the

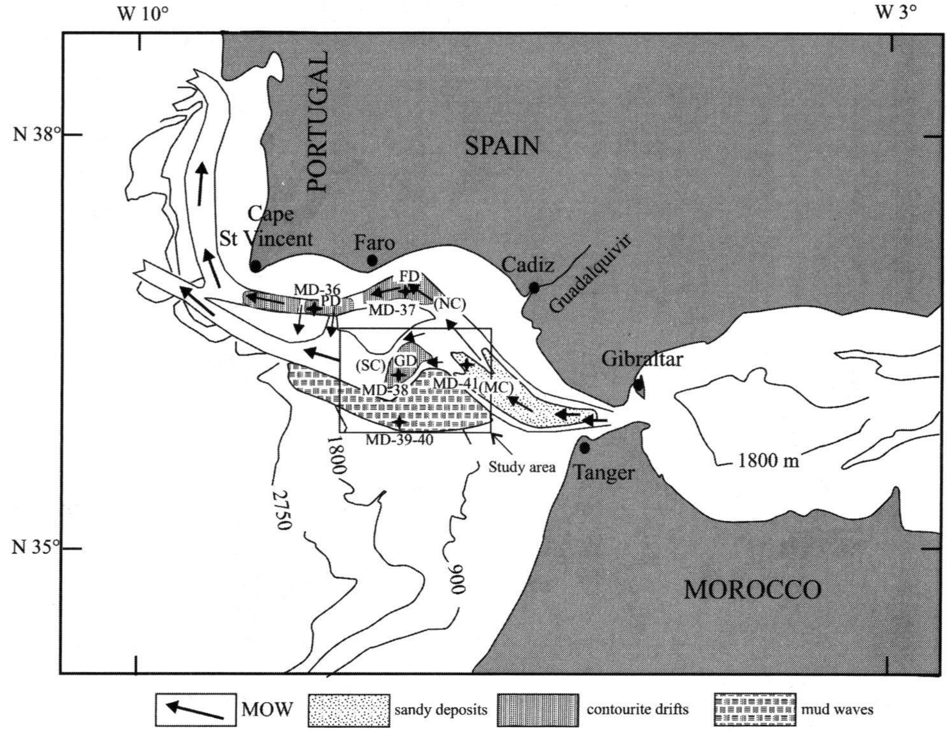

Fig. 1. General map of the Gulf of Cadiz showing the general circulation of the MOW and location of cores MD99–2336, MD99–2337, MD99–2338, MD99–2339, MD99–2340, and MD99–2341. Arrows indicate MOW direction. FD - Faro drift. GD - Guadalquivir drift. PD - Portimão drift.

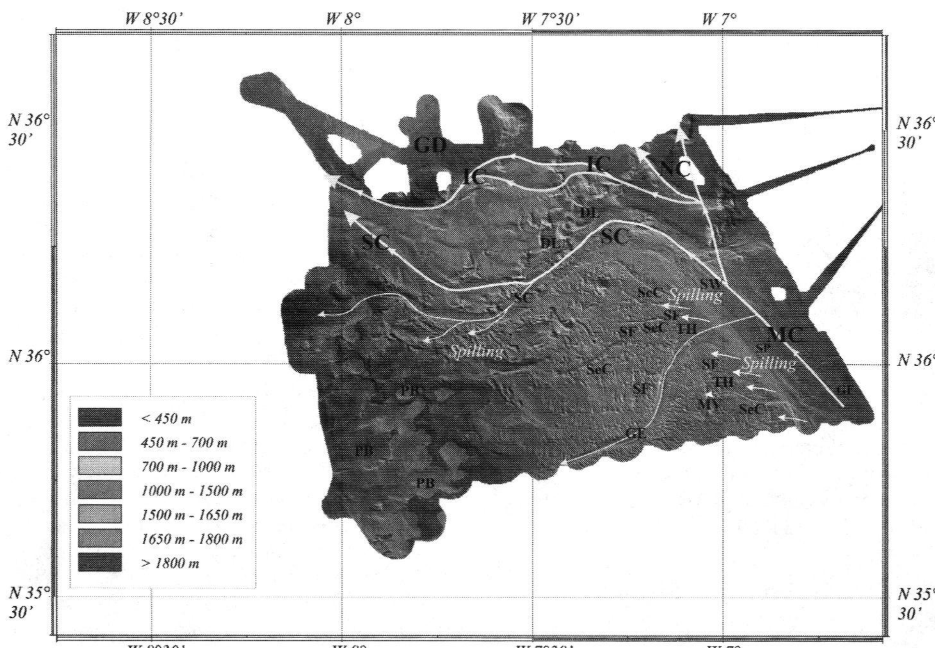

Fig. 2. High-resolution (30 m x 30 m grid) bathymetric map of the south part of the Gulf of Cadiz extending west of Gibraltar. DL - Lineaments of diapirs and rock outcrops. GD - Guadalquivir drift. GE - Gil Eanes channel. GF - Giant erosional features. IC - Intermediate MOW channel. MC - Major MOW channel. MV - mud volcano. NC - North MOW channel. PB - Ponded basins (ancient sediment failures). SC - South MOW channel. SeC - Secondary channel. SF - sediment failure. SP - sand patches. SW - sediment waves. TH - topographic high. Arrows indicate MOW pathway. Map produced using Caraibes software from IFREMER. Original color image appear at the back of this volume.

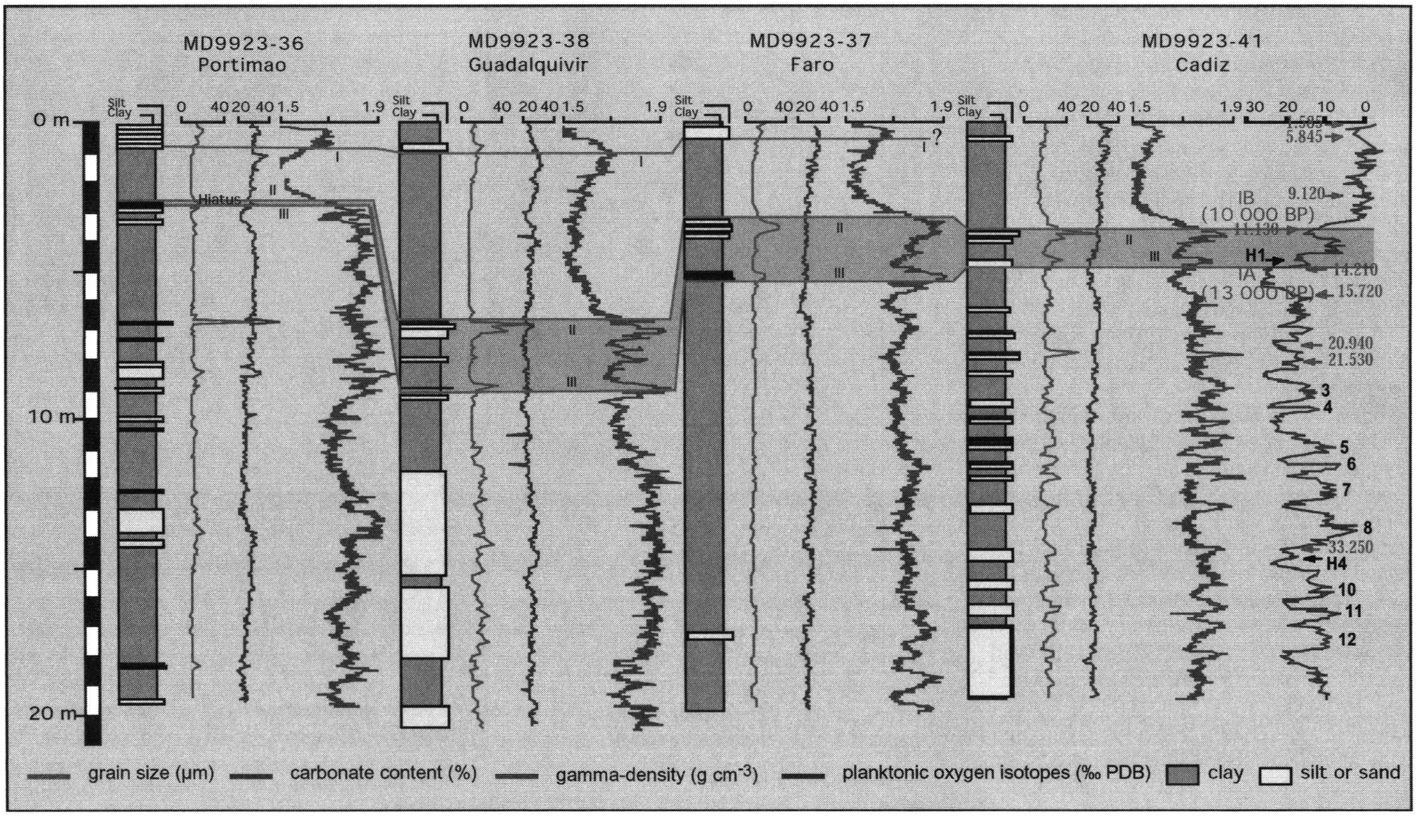

Fig. 3. Synthetic description and stratigraphic correlation for cores MD99–2336, MD99–2337, MD99–2338, and MD99–2341. The red arrows indicate levels of ^{14}C AMS dating on planktonic foraminifers in core MD99–2341. Black digits are Interstadial and Heinrich Event numbers. Original color image appears at the back of this volume.

1755 Lisbon earthquake [*Zitellini et al.*, 1999]—with their epicenter located in the Gulf of Cadiz or in the neighboring areas, and related to the activity of the accretion prism, probably contributed strongly to the triggering of these slope failures.

They also could be responsible for pockmark formations. These instabilities could be at the origin of the formation of secondary channels such as the Gil Eanes channel by retrogressive erosion. The most western part of the map shows circular to egg-shaped depressions (PB in Figure 2), interpreted as large sediment failures heading westward, and finally forming small ponded basins. The recent discovery of methane hydrates, cold seeps, and gas bubbles in sediment cores from pockmarks suggests that sediment instabilities could also be promoted by methane clathrates fluidizing [*Somoza et al.*, 2002].

Past Circulation and Paleoclimatic Records

Six 20-m-long cores have been collected during the IMAGES V cruises on the high sedimentation rate zones (Figures 1 and 3): the Portimão drift (MD99–2336), the Faro drift (MD99–2337), the Guadalquivir drift (MD99–2338), a mud-wave field (MD99–2339 and MD99–2340), and a landward terrace of the northern channel (NC, MD99–2341). Detailed sedimentological analysis shows that the cores comprise successions of alternating fine- and coarse-grained contourites. Coarse-grained contourites are deposited during periods of increased MOW velocity [*Gonthier et al.*, 1984]. Correlations with shorter cores [*Faugères et al.*, 1985b] suggest that three major periods of MOW acceleration are evidenced in the cores, except on the Portimão drift, where a sedimentary hiatus exists for the interval Boelling-Younger Dryas.

The three periods are noted as peak contourites I, II, and III in Figure 3 and correspond, respectively, to ages of ca. 3000 yrs BP, 10,000–11,000 yrs BP (Younger Dryas and termination IB), and 13,000–15,000 yrs BP (Last Isotopic Maximum and Heinrich Event H1), on the radiocarbon time scale [*Vergnaud Grazzini et al.*, 1989]. During these periods, coarse-grained contourites are associated with high benthic ^{13}C levels and high (smectite + kaolinite)/(illite + chlorite) ratios [*Vergnaud-Grazzini et al.*, 1989]. These periods of MOW intensification are also recorded in benthic faunal and isotope data from the upper Portuguese margin [*Schönfeld and Zahn*, 2000] and correspond to major Northern Hemisphere ice-melting phases with better oxygenation of intermediate waters in the Gulf of Cadiz following the Last Glacial Maximum (LGM, 18,000 yrs BP, or isotopic stage 2).

The period just following the LGM (17,000–15,000 yrs BP) and intervals between 13,000–11,400 yrs BP and 9000–5000 yrs BP are characterized by a finer sedimentation, suggesting a MOW of lesser intensity. The new IMAGES cores confirm the previous results about change in MOW activity since the LGM, and extend the MOW record back in time to 50,068 (MD99–2341) and 91,645 (MD99–2336) calendar years. The average sand content is higher prior to the last Glacial-Interglacial Transition in cores MD99–2338 and MD99–2341 than during the Holocene.

A backward extrapolation of the sand content variations from LGM to the present suggests that MOW velocity was probably higher during isotopic stage 3 than presently. It progressively decreased until LGM for the depth interval between 500–1200 m. This suggests an intensification of MOW during ice melting periods, similar to what happened after LGM. Pulses of energetic MOW during major cold periods (Stadials) are displayed by sand content maxima and contourite beds that alternate with periods of lesser intensity during Interstadials 3 through 12 (Figure 3). This pattern remains consistent further back in time. Oxygen isotope stage 4 in core MD99–2336 (1250–1405 cm) again shows higher sand contents and a bundle of contourite beds.

Gulf of Cadiz is Key

These data suggest that the Gulf of Cadiz is a key area to study this climatic record. Changes and pulses in MOW intensity are accurately recorded by deep-sea sedimentation and related to climatic changes. The sensitivity of the Gulf's sedimentary systems is due to the very strong current, in that the amplitude of change in velocity is sufficiently large to be recorded accurately. Simultaneously, particle supply is high and allows high sedimentation rates that facilitate a high temporal resolution to monitor millennial variations.

Reconstruction of the history of MOW activity is a key point for understanding recent global climatic changes and climate regulation during the Quaternary. The rate of MOW advection presumably is involved with North Atlantic thermohaline circulation THC [*Reid*, 1979], even though the sensitivity of modern THC-to-variable-MOW inputs is controversial [*Johnson*, 1997; *Rahmstorf*, 1998]. Nonetheless, under different—i.e., glacial—conditions with a weakened THC, MOW may well prove to be a key component to understanding rapid climatic changes and climate regulation. The dense Mediterranean outflow increases the density of cold Atlantic deep-water masses, and it may stabilize, or in cases of decreased MOW advection, destabilize the thermohaline circulation, and trigger climate change.

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Workshop Highlights Iron Dynamics in Ocean Carbon Cycle

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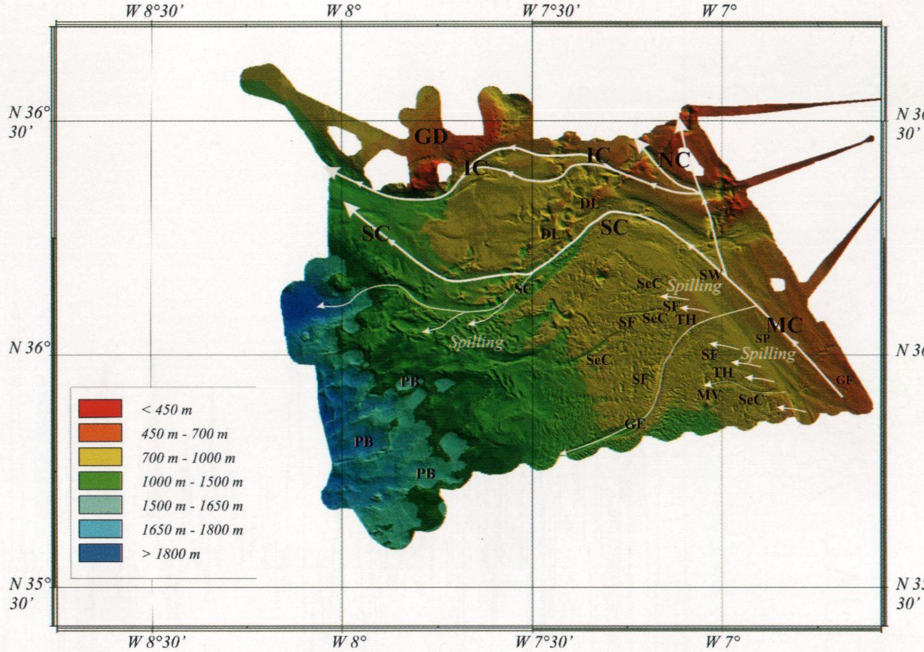
The role of iron in regulating the flux of carbon through the surface layer of the ocean has become increasingly apparent during the past 15 years. Before that time, the analytical challenges of measuring trace (parts per trillion) iron concentrations from iron ships using gear suspended on an iron wire precluded oceanographers from making accurate measurements. Laboratory experiments were invariably conducted with samples that were seriously contaminated with elevated iron concentrations. We now recognize, through greatly improved methodologies, that iron is a key regulator of phytoplankton primary production throughout the ocean. Small changes in iron concentration may produce large variations in the export of particulate organic carbon from the ocean's sunlit surface layer into deep-sea sediments. These variations in carbon export may occur over glacial/interglacial cycles at a scale sufficient to influence the flux of carbon dioxide from the atmosphere to the ocean. Such processes have been hypothesized to be an important driver of the changes in atmospheric carbon dioxide concentration that have been recorded in ice cores over the past 400,000 years.

Understanding the role of iron in the ocean biogeochemical cycle of carbon is essential for predicting long-term changes in the Earth's radiation budget. Adding iron to biogeochemical models has dramatically improved our ability to simulate ecosystem processes in the ocean. Basin- to global-scale models can now reproduce many features of the observed dissolved iron, macronutrient, and phytoplankton distributions. However, there are still a number of large uncertainties in our understanding of iron chemistry and its effects on oceanic biology. Reducing these uncertainties would be one of many key steps that are required to prognostically model ocean biogeochemical cycling and the marine ecosystem linkage to climate change.

A U.S. JGOFS Workshop on Iron Dynamics in the Carbon Cycle was held at the Monterey Bay Aquarium Research Institute in Moss Landing, California, to address these issues. Here, we present some of the major highlights and recommendations.

Iron Distributions

Perhaps the most pressing need is for an expansion of the global data base of dissolved iron distributions in the oceans. These measurements are needed both to initiate models and to identify processes not contained in models (see full meeting report for examples). Such an iron data base has not been accumulated because of the difficulties in measuring exceedingly low levels of iron (surface concentrations <0.1 nM and ocean mean concentration ~0.7 nM). Systematic variations in iron concentration exist, but there are no basin-scale sections of iron concentration that would allow us to define the spatial resolution that is required for a global survey. Significant progress has been made in developing techniques to make large numbers of iron measurements in seawater. It was concluded that, with modest additional efforts at inter-calibration, it would be feasible to map distributions of iron as a component of other global survey programs. Several sections would define the measurement requirements for future surveys.



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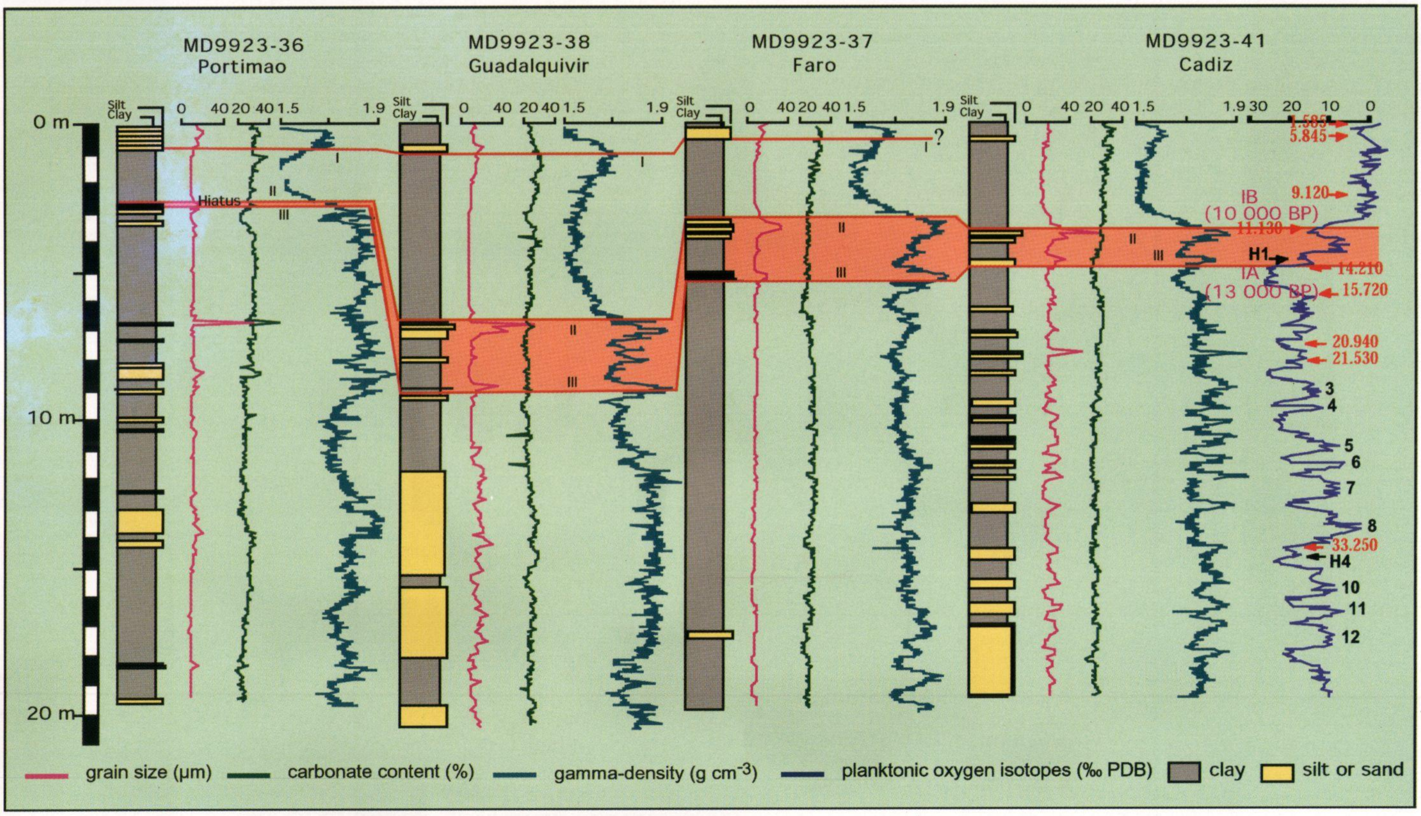

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