On the depth of anthropogenic CO$_2$ penetration in the Atlantic and Pacific Oceans

Anthropogenic CO$_2$
Tritium
Radiocarbon
Atlantic
Pacific

CO$_2$ anthropogénique
Tritium
Carbone radioactif
Atlantique
Pacifique

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ABSTRACT

This paper discusses the depth of penetration of anthropogenic CO$_2$ in both the Atlantic and Pacific Oceans based on carbonate data in the literature. The results indicate that in the Atlantic Ocean the excess CO$_2$ has penetrated through the entire water column in the northern North Atlantic, to roughly 1 000 m in the equatorial region, to over 1 800 m around 40°S, and to less than 200 m around 65°S, but penetration deepens again around the Antarctic Continent. The penetration in the Pacific Ocean is generally shallower than in the Atlantic Ocean, with the deepest penetration (over 1 200 m) found in the northwest North Pacific and in regions around 45°S. The shallowest penetration (to less than 400 m) is found in the Eastern equatorial Pacific and in regions around 65°S. Depth of penetration of anthropogenic CO$_2$ appears to have been controlled by such factors as bottom water formation in the North Atlantic, upwelling in the Eastern Atlantic, the equatorial Pacific and near 65°S, and vertical mixing in western boundary areas. These results compare well with results implied from tritium and C-14 distributions.

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RÉSUMÉ

Profondeur de pénétration du CO$_2$ anthropogénique dans les océans Atlantique et Pacifique

La profondeur de pénétration du CO$_2$ anthropogénique dans l'Océan Atlantique et dans l'Océan Pacifique est discutée dans cet article, à partir de données de carbonate obtenues dans la littérature. Les résultats indiquent que, dans l'Océan Atlantique, l'excès de CO$_2$ a traversé toute la colonne d'eau dans la partie nord, a pénétré jusque vers 1 000 m dans la région équatoriale, jusqu'à plus de 1 800 m autour de 40°S, et à moins de 200 m autour de 65°S, mais la pénétration s'accentue à nouveau autour du continent antarctique ; dans l'Océan Pacifique, la pénétration est généralement plus superficielle que dans l'Atlantique, la plus profonde (plus de 1 200 m) étant trouvée au nord-ouest du Pacifique Nord et dans les régions voisines de 45°S. La plus faible pénétration (moins de 400 m) est trouvée à l'est du Pacifique équatorial et dans les régions voisines de 65°S. La profondeur de pénétration du CO$_2$ anthropogénique paraît avoir été contrôlée par des facteurs tels que la formation d'eau de fond en Atlantique Nord, l'upwelling dans l'Atlantique oriental, le Pacifique équatorial et vers 65°S, le mélange vertical dans les régions limites occidentales. Ces résultats sont en bon accord avec ceux obtenus à partir des répartitions du tritium et du ^{14}C.

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INTRODUCTION

Recently it has been shown that the oceanic penetration of excess (anthropogenic) CO_2 can be calculated using carbonate data (Brewer, 1978 ; 1979 ; Chen, Millero, 1978 ; Chen, Pytkowicz, 1979 ; Jones, Levy, 1981 ; Kanamori, Ikegami, 1982 ; Chen et al., 1982 ; Chen, 1982 a, b ; 1984 ; Papaud, Poisson, 1986). Because the method is subject to large uncertainties, the accuracy of the results is not known (Chen, Millero, 1979 ; Chen, Pytkowicz, 1979 ; Shiller, 1981 ; Chen et al., 1982 ; Broecker et al., 1985). However, the precision of the method is adequate to show the excess CO_2 signal. The abundant carbonate data in the literature can thus be used to supplement the tracer data in showing oceanic mixing features for waters formed in the last 130 years (Chen, 1980). The distribution of other man-made gaseous pollutants in the oceans can be estimated by following the excess CO_2 signal.

METHOD

The method of computation and its limitations have been described in detail elsewhere (Chen, Millero, 1979 ; Chen, Pytkowicz, 1979 ; Baes, 1981 ; Chen et al., 1982 ; Chen, 1982 b ; 1984 ; Cline et al., 1985 ; Poisson, Chen, in prep.). The method involves a back-calculation of the CO_2 concentration of a parcel of seawater to its initial concentration at the sea surface by correcting for changes due to the decomposition of organic material and dissolution of carbonate particulates.

Specifically, the method assumes that a water parcel maintains a fixed degree of saturation with respect to atmospheric CO_2 at the sea surface. Respiration and carbonate dissolution add carbon dioxide to the water parcel after it sinks. The respiration-induced increase in CO_2 can be calculated from the oxygen data using the Redfield ratio (Redfield et al., 1963) while CO_2 changes due to carbonate dissolution can be calculated from the alkalinity changes. By correcting the CO_2 data for these changes, estimates can be made of the CO_2 concentration of the water parcel when it was last in contact with the atmosphere. These back-calculated CO_2 concentrations of waters with various ages are then compared with each other and with the contemporary surface CO_2 concentrations to obtain the oceanic CO_2 increase. The sources of data are as follows :

Atlantic Ocean

International Geophysical Year (Ob, 1956-1958) 39 stations ;
9th Japanese Antarctic Research Expedition (Fuji, 1967-1968) 5 stations ;
Meteo 23 (Meteo, 1971) 5 stations ;
Knorr (Knorr, 1972) 1 station ;
International Weddell Sea Oceanographic Expedition (Melville, 1973) 3 stations ;
GEOSECS (Knorr, 1972-1973) 58 stations ;
Weddell Polynya Expedition (Somov, 1981) 24 stations.

Pacific Ocean

International Geophysical Year (Ob, 1956-1958) 97 stations ;
Eltanin Cruise 34 (Eltanin, 1968) 20 stations ;
YALOC 69 (Yaloc, 1969) 31 stations ;
Eltanin Cruise 41 (Eltanin, 1969-1970) 22 stations ;
ANTIPODE 15 (Melville, 1971) 4 stations ;
KH-71-5 (Hakuho Maru, 1971) 55 stations ;
GEOSECS (Melville, 1973) 72 stations ;
KH-75-4 (Hakuho Maru, 1975) 12 stations ;
INDOPAC (Melville, 1976) 46 stations ;
KH-78-3 (Hakuho Maru, 1978) 7 stations ;
CO_2 Dynamics Cruise ENP (Miller Freeman, 1981) 10 stations ;
CO_2 Dynamics Cruise WNP (Discoverer, 1982) 10 stations ;
Outer Continental Shelf Environmental Assessment Program (Polar Sea, 1983) 2 stations.

RESULTS AND DISCUSSION

The lower boundary of the excess CO_2 penetration is defined as the depth at which the excess CO_2 concentration is less than 5 μmol/kg, approximately 12 % of the magnitude of the signal. Because of the uncertainty of the method and the large vertical spacing of the samples, the lower boundary may be up to 150 m too deep or up to 300 m too shallow. The distribution of this lower boundary in the Atlantic Ocean is shown isogrammatically in Figure 1. The results indicate that anthropogenic CO_2 has penetrated below the thermocline everywhere in the Atlantic. For regions north of the Antarctic Front, the shallowest penetration (1 000 m) occurs in the equatorial region off West Africa, reflecting the high rate of upwelling of old deep water (Stuiver, 1980). Deeper penetration
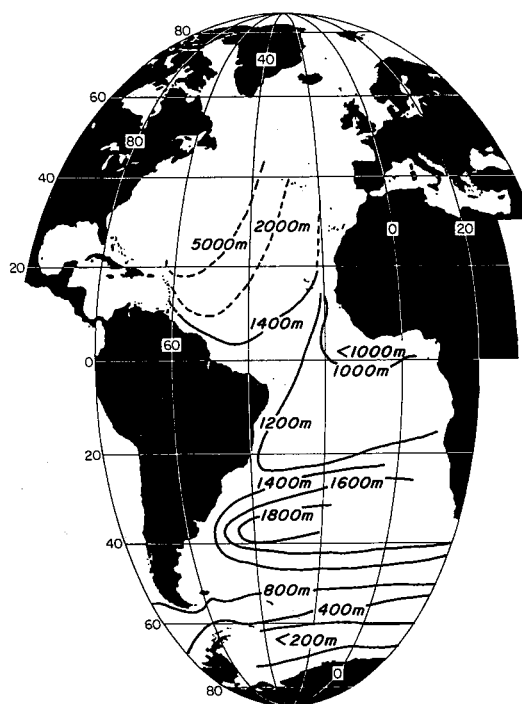

Figure 1
Isogram of the lower boundary of excess CO_2 penetration in the Atlantic Ocean.

(1 200 m) occurs on the western side. Clearly, horizontal advection of young waters from higher latitudes, rather than vertical mixing in the equatorial region, contributes to the excess CO_2 being found at such depth in the equatorial Atlantic Ocean.

The deepest penetration of excess CO_2 in the Atlantic occurs in the northwest region where the excess CO_2 has reached the sea floor. Analysis of tritium and He-3 data (Roether, Munnich, 1974 ; Ostlund et al., 1976 ; Jenkins, 1980 ; Jenkins, Rhines, 1980 ; Sarmiento et al., 1982) shows that bomb-produced tritium has also reached the sea floor in this region. However, the excess CO_2 results are probably not reliable north of 20°N because insufficient data are available for our calculation. Analysis of the excellent TTO (Transient Tracers in the Ocean) and winter Hudson data should allow us to improve the quality of our results in the future.

Other than the northwest Atlantic Ocean, the deepest excess CO_2 penetration occurs near 40°S, especially in the region off South America (to 1 800 m) where the Falkland Current joins the Brazil Current Extension (Gordon et al., 1977 ; Reid et al., 1977). This is a region of low potential vorticity and corresponds to the Subantarctic Mode Water (McCartney, 1982). Intensive vertical mixing in the Drake Passage apparently transports the excess CO_2 to subsurface waters which are then advected northward as a western boundary current which enters the South Atlantic near 40°S, 55°W (Chen, 1982 b ; McCartney, 1982).

Winter surface sea ice coverage and intensive upwelling of old Circumpolar Deep Water (CDW) in the Weddell Sea (Gordon et al., 1984) prevent excess CO_2 from moving freely across the air-sea boundary or being advected downward. As a result, little excess CO_2 is found below 200 m in the Weddell Gyre (Poisson, Chen, in press). This finding contradicts the work of Bolin (1983) who believed that the Antarctic Deep Water may have been significantly affected by the net transfer of CO_2 to the sea. However, the excess CO_2 seems to have penetrated the entire water column on the Antarctic continental shelf where the upwelling of CDW is not evident.

Figure 2 shows an isogram map of the lower boundary of tritium penetration in the Atlantic (0.1 TU or higher) based upon the GEOSECS data (Ostlund et al., 1976). These contours show a gross similarity with the excess CO_2 contours given in Figure 1 but with a coarser resolution, because there are fewer tritium stations than carbonate stations. The excess CO_2 generally reaches a depth several hundred meters deeper than tritium does. It should be noted, however, that the recent TTO results (Ostlund, 1983) show a deeper tritium penetration than that found during GEOSECS. Also, some bottom samples collected in the Weddell Sea contain some tritium (Michel, 1978).

For areas north of 40°S, the pre-industrial, pre-bomb (pre-1958) Atlantic surface water ΔC-14 values have been estimated to be about − 40 ‰ (Stuiver, 1980). A higher value indicates contamination by bomb-produced C-14. An isogram map of the depth where ΔC-14 concentration equals − 40 ‰ is shown on Figure 3 (data from Ostlund et al., 1976 ; Stuiver, Ostlund, 1980). Waters above this have all been contaminated by bomb-produced C-14. Although the shape of the
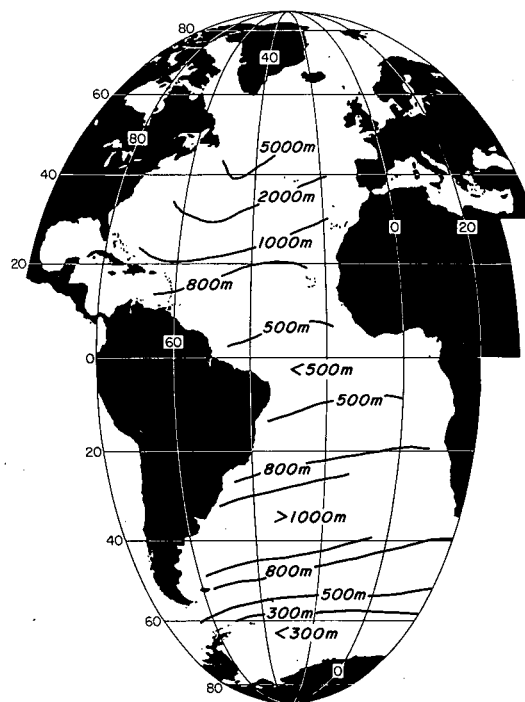

Figure 2

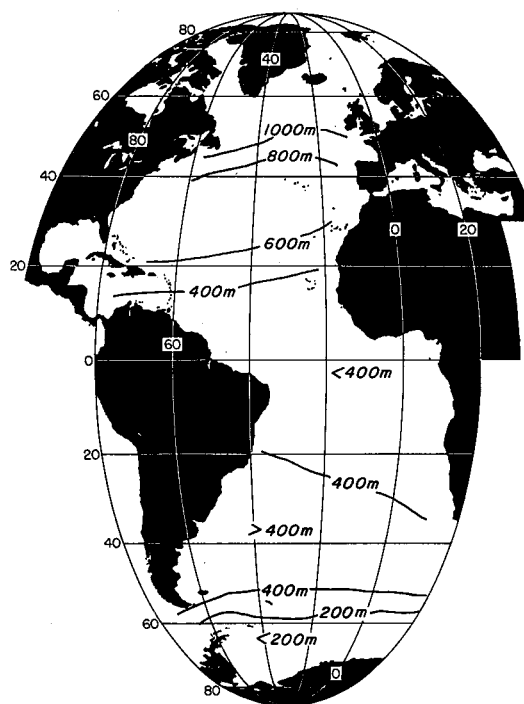*Isogram of the lower boundary of tritium penetration in the Atlantic Ocean.*

Figure 3

Isogram of the depth in the Atlantic Ocean where the ΔC-14 concentration equals − 40 ‰.

contours are somewhat similar to those shown on Figures 1 and 2, excess CO_2 and tritium evidently have penetrated much beyond the depth at which ΔC-14 concentration equals to − 40 ‰. This is to a degree to be expected because excess CO_2 began to be produced over a century before bomb C-14 was produced. Further, we believe waters formed in the

high latitudes probably all had a ΔC-14 concentration lower than − 40 ‰. Consequently, a lower ΔC-14 concentration should be expected for pre-industrial waters formed in the polar regions. These waters advect quickly to the equatorial region, carrying with them excess CO_2 and a ΔC-14 concentration lower than − 40 ‰.

The pre-industrial, pre-bomb ΔC-14 concentration in the Southern Ocean is indeed closer to − 110 ‰, based on the measurements of summer samples (Broecker *et al.*, 1960 ; Broecker, 1963). Winter concentrations are probably even lower because vertical convection brings up old waters with low ΔC-14.

The isogram map of the depth where ΔC-14 equals − 110 ‰ in the waters above the Antarctic Intermediate Water (AAIW) is shown in Figure 4. The relative distribution of these contours shows somewhat better agreement with those of the excess CO_2
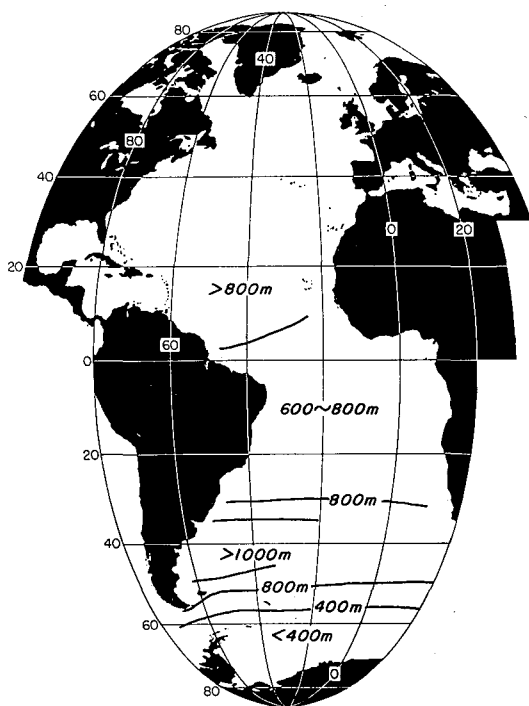

Figure 4

Isogram of the depth in the Atlantic Ocean where the ΔC-14 concentration equals − 110 ‰.

distributions. Waters found in the northern North Atlantic Ocean all have a ΔC-14 value higher than − 110 ‰ and the preformed ΔC-14 concentrations of these waters are probably between − 40 and − 110 ‰. At present, the subsurface waters in the northern North Atlantic Ocean have all been affected by the bomb-C-14.

An isogram map of the lower boundary of the excess CO_2 penetration in the Pacific Ocean is shown in Figure 5. The major difference between the Pacific and the Atlantic Ocean is that excess CO_2 does not penetrate below the thermocline in the Pacific Ocean because there is no bottom water formation in the North Pacific. The shallowest penetration outside of the Southern Ocean occurs in the eastern equatorial region where the excess CO_2 only penetrates to 400 m, or shallower. Because few data are available
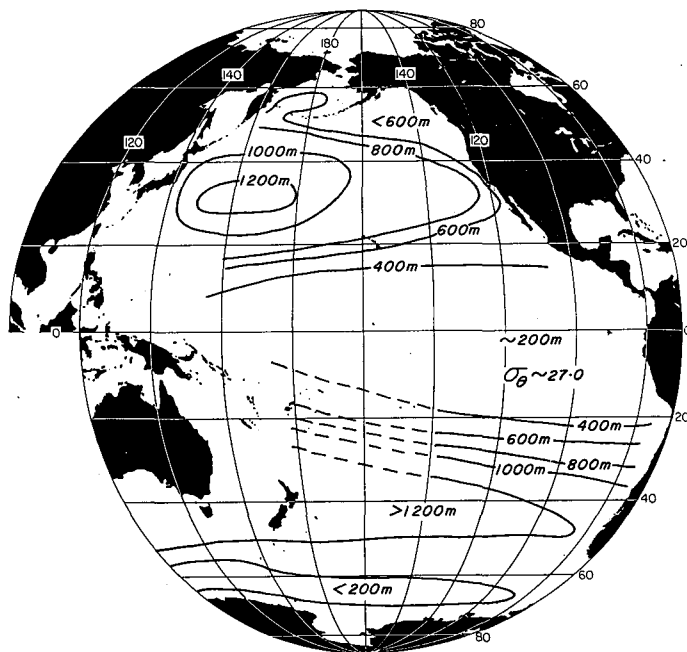

Figure 5

Isogram of the lower boundary of excess CO_2 penetration in the Pacific Ocean.

for the complex oceanic region in the Western equatorial Pacific, results there are less reliable. The general trend, however, indicates a deeper penetration (800 m) in the Western Pacific. Overall, the excess CO_2 penetrates to a shallower depth in the equatorial Pacific than in the Atlantic, perhaps reflecting the higher equatorial upwelling rate in the Pacific (Broecker *et al.*, 1978 ; Stuiver, 1980 ; Wyrtki, 1981 ; Quay *et al.*, 1983) and less influence of the newly formed water advected from the north (Fine *et al.*, 1981).

Similar to what was found in the Weddell Sea, intensive upwelling prevents excess CO_2 from reaching more than 200 m deep in the region around 65°S. The excess CO_2 penetrates deeper further south, and reaches more than 1 000 m off Cape Adare at the northwest corner of the Ross Sea.

The deepest excess CO_2 penetration in the South Pacific occurs around 45°S near where the Subantarctic Mode Water is located (McCartney, 1982), but the depth of penetration is slightly shallower than that found in the South Atlantic Ocean. The deepest penetration in the North Pacific occurs in the confluence of the Kuroshio and Oyashio currents. This is the region off Japan near the area of circulation of the North Pacific variety of the Subtropical Mode Water (Tsuchiya, 1982 ; McCartney, 1982). Here excess CO_2 has penetrated to a depth of more than 1 200 m.

Figure 6, based on the GEOSECS data (Ostlund *et al.*, 1979 ; Fine *et al.*, 1981) is an isogram map of the depth where tritium equals to 0.1 TU. The similarity in distribution with the excess CO_2 results is striking.

Based on the oceanic seawater data of Broecker *et al.* (1960) and Broecker (1963), and the coral data of Druffel (1980) and Toggweiler (1983) the pre-industrial ΔC-14 concentration for low and mid-latitude

Figure 6
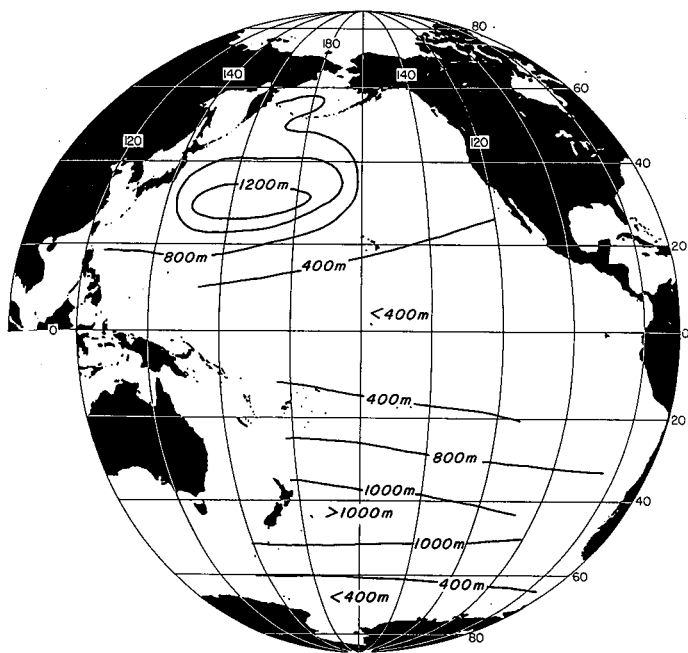*Isogram of the lower boundary of tritium penetration in the Pacific Ocean.*

al. (1960) and Broecker (1963), and the model calculations of Toggweiler (1983)]. Figure 8 shows an isogram map of the depth at which ΔC-14 equals $- 110$ ‰. The results north of 30°N and south of 30°S agree better with the excess CO_2 results shown in Figure 5, but near Equator the excess CO_2 has not reached the depth where ΔC-14 equals $- 110$ ‰.

Figure 8
Isogram of the depth in the Pacific Ocean where the ΔC-14 concentration equals $- 110$ ‰.

waters in the Pacific Ocean is probably also about $- 40$ ‰, similar to the value in the Atlantic Ocean. Figure 7 derived from the data of Ostlund *et al.* (1979) and Ostlund and Stuiver (1980), shows an isogram map of the depth where the ΔC-14 concentration equals to this value. The agreement with the excess CO_2 results is rather good between 30°S and 30°N. At higher latitudes the agreement is poor because the subsurface waters in the Subarctic and Antarctic regions have a pre-industrial ΔC-14 concentration near $- 110$ ‰ [based on the seawater data of Broecker *et*
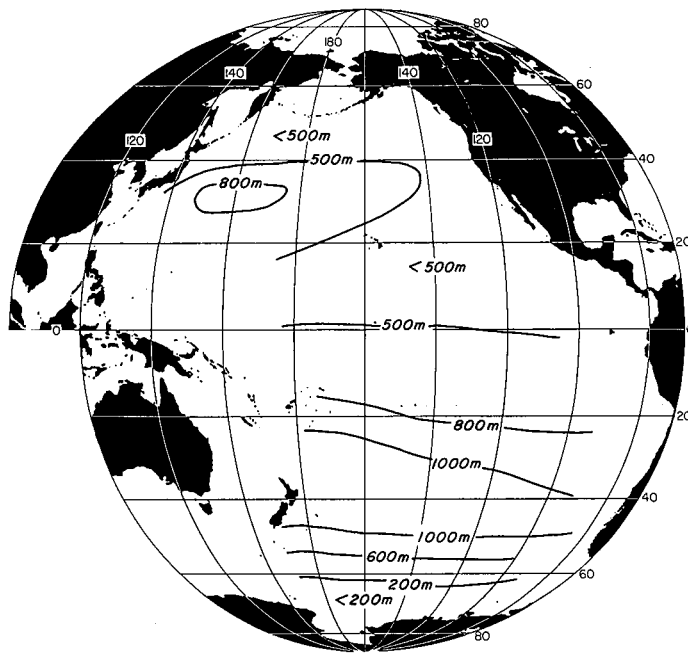
It should be emphasized that the back-calculation method is subject to large uncertainties (Brewer, 1978 ; Chen, Millero, 1978 ; 1979 ; Chen, Pytkowicz, 1979 ; Shiller, 1981 ; Chen *et al.*, 1982 ; Chen, 1982 *a* ; *b* ; 1984 ; Broecker *et al.*, 1985). Although a recent study by Cline *et al.* (1985) indicates that the excess CO_2 results agree, quantitatively, with results calculated using freon data in the North Pacific Gyre, we have not been able to quantitatively correlate the excess CO_2 results with tritium and ΔC-14.

CONCLUSION

The lower boundary of anthropogenic CO_2 penetration based on carbonate data in the literature has been shown for the Atlantic and Pacific oceans. The results indicate that the distribution of excess, anthropogenic CO_2 follows the large-scale movements of water masses such as vertical mixing in the northwest North Atlantic, upwelling, and Mode Water formation. The. deepest penetration is found in the northwest North Atlantic where the entire water column has been contaminated by the excess CO_2. Other regions of deep penetration are the three areas where the Subtropical Mode Waters are found : the northwest Pacific off Japan, around 40°S in the Atlantic, and
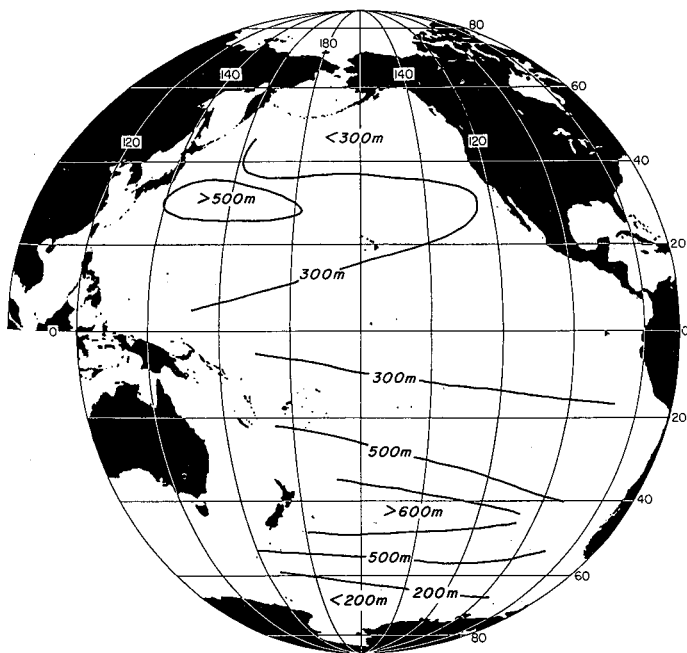

Figure 7
Isogram of the depth in the Pacific Ocean where the ΔC-14 concentration equals $- 40$ ‰.

around 45°S in the Pacific. The shallowest penetration areas are around 65°S and in the equatorial region in both oceans. The excess CO_2 has penetrated deeper in the Atlantic Ocean than in the Pacific.

Acknowledgements

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