

RADIOCARBON RESERVOIR AGE VARIATIONS IN THE SOUTH PERUVIAN UPWELLING DURING THE HOLOCENE

Michel Fontugne¹ • Matthieu Carré² • Ilhem Bentaleb² • Michèle Julien³ • Danièle Lavallée³

ABSTRACT. In Quebrada de los Burros in coastal southern Peru (Tacna department), human settlements containing shells and charcoal deposits have been excavated since 1995. The sea surface ¹⁴C reservoir ages, estimated by calculating the difference of ¹⁴C age between marine shells and terrestrial organic materials, exhibit high values during the lower and middle Holocene and decrease abruptly after 4000 cal BP. The increase of reservoir age at around 7000–8000 cal BP suggests an enhancement of Peruvian coastal upwelling intensity and changes in ocean circulation at intermediate depth.

INTRODUCTION

Recent studies in paleo-oceanography and paleoclimate focused on the radiocarbon reservoir age (*R*) of surface seawaters since they could provide indications on oceanic circulation both for surface and/or deep-intermediate waters (Siani et al. 2000, 2001; Reimer and McCormac 2002; Southon et al. 2002). The classical approach consists in measuring the ¹⁴C age difference between a terrestrial organic vegetal sample and a contemporaneous marine shell. Such a conjunction of samples is not often encountered except in coastal archaeological sites.

Here, we present new results from the southern Peruvian coast which provide some information about the upwelling system variability and its relation with El Niño events.

MATERIAL AND METHODS

Sample Location

Samples were collected at Quebrada de los Burros (18°1'S; 70°50'E) and neighboring sites (Cañon site and Inca site) both located in the Tacna department in the northern Atacama Desert (Figure 1). Quebrada de los Burros is a narrow valley oriented roughly north/south. This valley is about 150 m above mean sea level and the archaeological site is located less than 1 km from the shore (see Lavallée et al. 1999a, b, for details; Fontugne et al. 1999). All the shells and organic matter samples come from a narrow area restricted to the gully and excavations (about 400 m × 50 m). At the mouth of Quebrada, on a marine terrace 10 m above present sea level, we collected also charcoal, wood, and shells in an Inca site. The Cañon site is located 500 m from the Quebrada de los Burros sites in a larger and parallel valley at the same elevation. Only in Quebrada, springs occur(ed) that created wetlands in very restricted areas and water availability for prehistoric people (Fontugne et al. 1999).

Sampling Procedures

Reservoir ages are generally estimated by calculating the difference of ¹⁴C age between marine shells and terrestrial organic materials supposed to be contemporaneous. However, many problems in estimation of marine reservoir ages have been due to problematical associations. In order to illus-

¹Laboratoire des Sciences du Climat et de l'Environnement, UMR 1572-CEA/CNRS, Domaine du CNRS, F-91198-Gif sur Yvette cedex, France. Corresponding author. Email: Michel.Fontugne@lsce.cnrs-gif.fr.

²Institut des Sciences de l'Evolution de Montpellier, UMR 5554, Place Eugène Bataillon CC064 F-34095 Montpellier cedex 5, France.

³Archéologie des Amériques, CNRS, Maison de l'Archéologie et de l'Ethnologie, 21, Allée de l'Université, F-92023-Nanterre cedex, France.

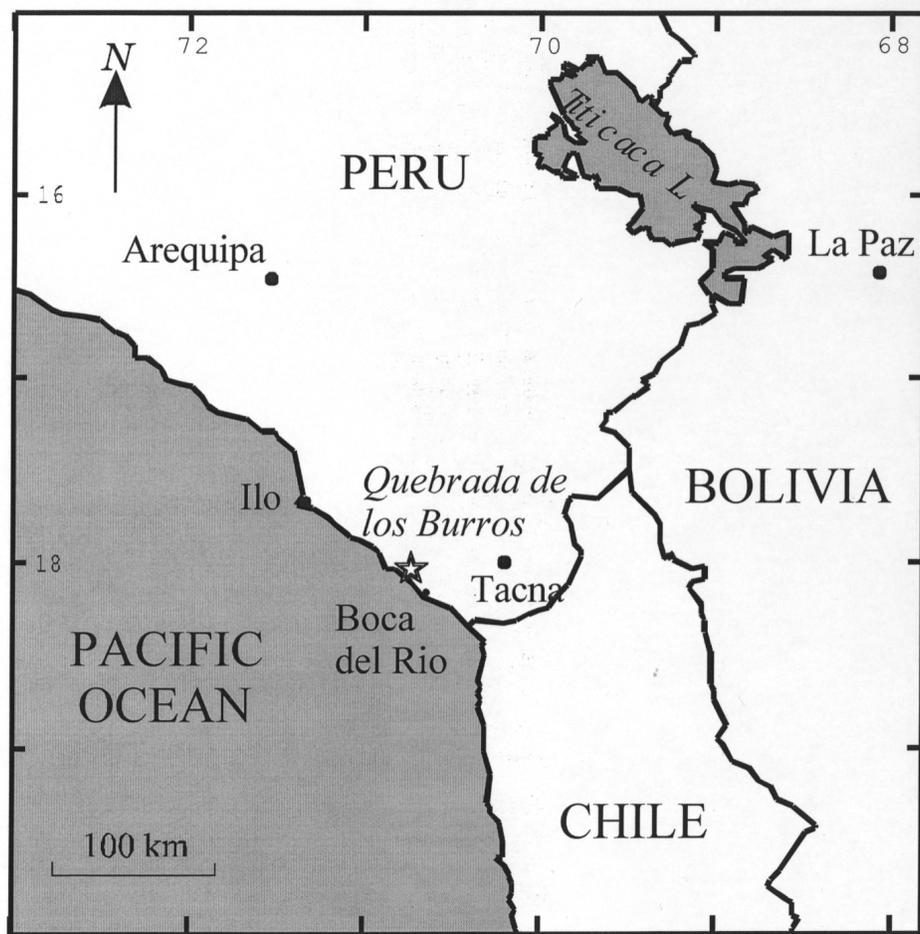


Figure 1 Location of the Quebrada de los Burros site

trate this difficulty, we used results of dating previously obtained at different locations of the archaeological site during different excavation campaigns. Associations were based on stratigraphical correlations or on archaeological interpretation attributing each settlement level to a cultural phase. Results reported in Table 1 led us to perform a specific sampling in order to avoid problems of the samples' location, and in interpretation of sedimentology and stratigraphy units in the site.

Paired samples of charcoals and marine shells (*Concholepas concholepas*, *Mesodesma donacium*) stratigraphically associated were selected in different archaeological levels. They were strictly in connection (charcoals were within the shell). We tried to select shells without any visible trace of alteration. Dating was performed on shell that contained micro-charcoals (less than 1 mm) using both β -counting and accelerator mass spectrometry (AMS) techniques.

Others samples were collected within 3 cross-sections in a gully within the Quebrada. These cross-sections have been already described by Fontugne et al. (1999) and Usselman et al. (1999). They contain mollusk shells eaten by man, associated with organic layers containing a mixture of plant detritus, with probably aquatic terrestrial plant remains and also charcoal powder, as revealed by pollen analyses. Here, too, samples were collected in connection. Results are in reported in Table 2.

Table 1 ¹⁴C conventional ages of marine shell and terrestrial organic samples, calibrated ages, and shell reservoir ages at Quebrada de los Burros, southern Peru. Samples were collected during different excavation campaigns and were not strictly in connection.

Laboratory nr	Sample nr	Unit nr	Nature	Conventional age	δ ¹³ C (‰)	Calibrated age	Cal BP (yr) range	Reservoir age
Gif-10634	5087	QLB 3	Organic layer	8040 ± 105	-19.7	8996	9254–8592	275 ± 121
Gif-11453	—	QLB23	Shell	8315 ± 60	0.0	—	—	—
GifA 97289	5092	A3 NIV 2B	Charcoal	6630 ± 70	-20.5	7548	7611–7336	215 ± 76
Gif-10689	5158	N2B	Shell	6845 ± 30	-0.2	—	—	—
Gif-10635	5066	QLB4	Organic layer	7320 ± 80	-14.9	8150	8326–7944	-10 ± 94
Gif-11450	—	QLB 20	Shell	7310 ± 50	-0.9	—	—	—
Gif-10636	5067	QLB5	Organic layer	6940 ± 60	-16.3	7725	7921–7615	155 ± 78
Gif-11451	—	QLB21	Shell	7095 ± 50	0.0	—	—	—
GifA 97287	5056	B3 NIV2A	Charcoal	6460 ± 60	-15.6	7416	7432–7252	350 ± 100
GifA 97288	5057	C1 NIV 2A	Charcoal	6510 ± 60	-22.0	7424	7552–7270	400 ± 100
Gif-10399	5021	N2a	Shell	6110 ± 80	-3.0	—	—	—

Table 2 ¹⁴C conventional ages of marine shell and terrestrial organic samples collected strictly in connection, calibrated ages, and shell reservoir ages at Quebrada de los Burros, southern Peru.

Laboratory nr	Sample nr	Unit nr	Nature	Conventional age	δ ¹³ C (‰)	Calibrated age	Cal BP (yr) range	Reservoir age
Gif-10633	5086	QLB2	Organic layer	8160 ± 70	-15.0	9030	9399–8781	700 ± 148
Gif-10400	5035	—	Shell	8860 ± 130	-1.0	—	—	—
Gif-10634	5087	QLB3	Organic layer	8040 ± 105	-19.7	8996	9254–8592	740 ± 126
Gif-10401	5031-2	—	Shell	8780 ± 70	0.3	—	—	—
Gif-10648	5088	QLB17	Organic layer	3700 ± 40	-15.0	4057	4146–3874	745 ± 57
Gif-10404	5011	—	Shell	4445 ± 40	0.3	—	—	—
GifA 99341	5323	D9/2inf	Charcoal	6090 ± 80	-25.3	6894	7179–6690	980 ± 113
GifA 99509	5323	D9/2inf	Shell	7070 ± 80	0.6	—	—	—
GifA 99576	5292	E9/2sup	Charcoal	6560 ± 90	-17.9	7430	7573–7272	920 ± 120
GifA 99510	5295	E9/2sup	Shell	7480 ± 80	0.6	—	—	—
Gif-10643	5080	QLB12	Organic layer	7390 ± 50	-15.3	8175	8330–8030	735 ± 58
Gif-10646	5083	QLB15	Shell	8125 ± 30	0.5	—	—	—
Gif-10645	5082	QLB14	Organic layer	6595 ± 75	-13.6	7234	7415–7278	565 ± 110
Gif-10647	5084	QLB16	Shell	7160 ± 80	0.7	—	—	—
Gif-10629	5074	Cañon	Charcoal	3120 ± 80	-25.3	3341	3473–3065	475 ± 120
Gif-10722	5074	Cañon	Shell	3595 ± 90	0.0	—	—	—
GifA 100347	5406	E5-6N4	Charcoal	6500 ± 80	—	7422	7558–7254	1290 ± 144
GifA 100348	5406	E5-6N4	Shell	7790 ± 120	—	—	—	—
Gif-11457	—	Site Inca/QLB31	Wood	375 ± 30	-22.9	455	484–313	675 ± 42
Gif-11456	—	Site Inca/QLB 31C	Shell	1050 ± 30	-0.5	—	—	—
GifA 100142	5373	DE9/fond N2	Charcoal	6090 ± 110	—	6894	7231–6670	550 ± 121
Gif-10649	5061	N2a	Shell	6640 ± 50	-0.4	—	—	—
Gif-10642	5079	QLB11	Organic layer	8650 ± 70	-13.4	9550	9888–9490	1075 ± 114
Gif-11452	—	QLB22	Shell	9725 ± 90	-0.1	—	—	—
GifA 100343	5383	B0C5/N4 5383	Charcoal	7360 ± 100	-16.5	8167	8349–7963	520 ± 135
GifA 100342	5383	B0C5/N4 5383	Shell	7880 ± 90	-0.4	—	—	—

Hardwater or Old Wood Effects

Hardwater effect and/or old wood effect are common problems in estimation of marine reservoir ages. In Quebrada, the hardwater effect could influence the aquatic plants, possibly contributing to these organic layers, and would result from dissolution of old carbonate and contamination by old bicarbonate or dissolved CO₂ that could be used by the plant through photosynthesis processes. This effect is highly improbable in a hyper-arid region and, secondly, because the volcanic origin of the substratum (Formacion Chocolate) covered by sand sediment, is devoid of carbonate.

Taking into account these observations and the coherence of these dates with those obtained for paired charcoal and shell in similar levels in the archaeological site, we admit that no aging due to hardwater effect occurs. Inversely, if we consider that such an aging would have occurred for these organic layers, it would imply a younger actual age and, consequently, a larger increase of sea surface reservoir age than we found. Such results would be hardly compatible with literature data or with other data obtained with charcoals and shells in Quebrada. Similarly, secondary alteration or recrystallization of shell carbonate would lead to the fixation of younger carbon and younger ages, meaning that our calculations of reservoir effect were underestimated.

The “old wood” problem results from the hyper-arid conditions in this region that promote long-term preservation of organic material which could be used by people. This effect gives low or negative R values like those observed by Kennett et al. (2002) in the same region. It does not apparently occur at Quebrada de los Burros.

Whatever we consider, if hardwater or old wood effects or shell recrystallization have affected one or both paired samples, it would lead to an actual marine reservoir age that would be higher than we estimate. R values reported in Table 2 have to be considered as minimal values.

Analytical Procedures

^{14}C dating was performed using beta-counting gas proportional counter and AMS facilities at Gif sur Yvette. Shells were cleaned using either dilute HCl (β -counting samples) or sandblaster followed by acid treatment for AMS samples (Tisnérat et al. 2001) in order to remove the superficial part of the shell that might have been re-crystallized (Vita-Finzi and Roberts 1984). Charcoals and organic layers were prepared using classical treatments. Results are expressed as conventional ages (Stuiver and Pollack 1977) and calibrated age according to Stuiver et al. (1998).

RESULTS AND DISCUSSION

Results of the first study are reported in Table 1. All R values are smaller than the mean ocean reservoir age (400 yr) and are not compatible with an upwelling pattern that always prevailed in this region during the Holocene period. This illustrates that sampling needs to be performed very carefully; moreover, in order to study reservoir ages variations, a specific sampling would be recommended. Comparison of dates obtained by long distance correlation between different archaeological levels at different places in these sandy excavations is very confusing. The Quebrada de los Burros site presents a low sedimentation rate and archaeological levels that are not very thick. In this context, a possible penetration of shell in the underlying archaeological level is probable.

All the results of the second sampling are reported in Table 1 and Figure 2. The chronology is derived from ^{14}C conventional ages of terrestrial organic origin and extends from the Inca period 375 ± 30 ^{14}C BP to 8650 ± 70 ^{14}C BP (455–9550 cal BP). No human settlements or organic deposits could be found between 375 and 3200 ^{14}C BP. During the early- and mid-Holocene, differences between ^{14}C ages of shell and charcoal (R values) are high, ranging between 700 and 1230 yr. The “old wood” problem, giving low or negative R values like those observed by Kennett et al. (2002) in the same region, do not apparently occur at Quebrada de los Burros. Nevertheless, lower R values were observed around 6090 and 6595 and 7390 and 7360 ^{14}C BP. Between 3000 ^{14}C BP and the present, reservoir ages dropped down to low values (less than 700 yr), in good agreement with modern values 590 ± 40 yr and in agreement with Stuiver and Braziunas (1993) and Owen (2002). The large variations observed for reservoir age imply that for dating archaeological sites, the use of modern ^{14}C reservoir age correction (as it is done generally) could introduce uncertainties greater than 500 yr.

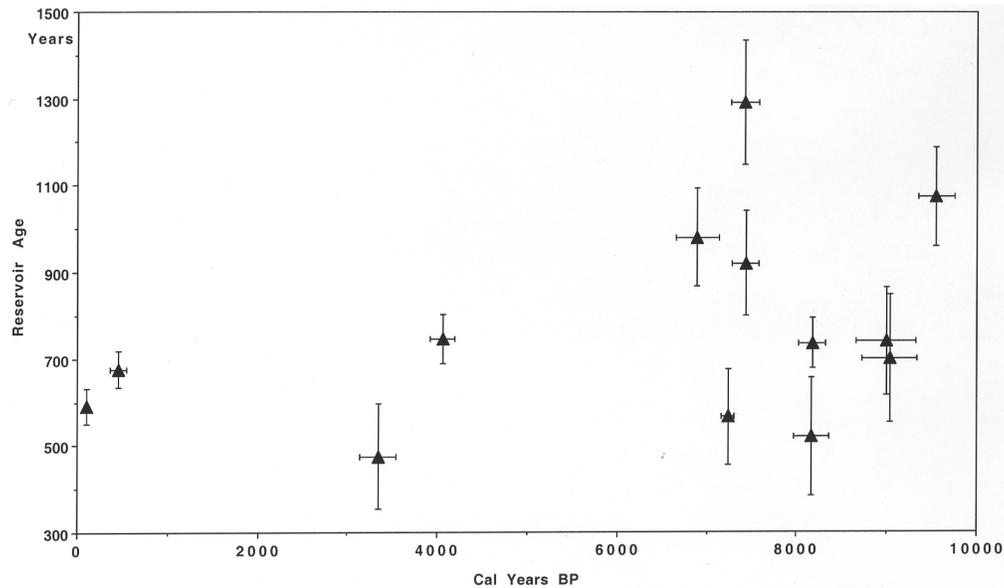


Figure 2 Variation of reservoir age of surface seawater versus time (¹⁴C cal BP). The errors quoted are 1 σ .

The increase of reservoir age in upwelling areas is generally interpreted as an enhancement of upwelling intensity which brings deeper waters to the surface. Such an interpretation corroborates the hypothesis developed by Fontugne et al. (1999). They suggest that reinforced upwelling would generate more fogs condensing at mid-altitude (600–1000 m) in the Andes. This precipitation provides enough humidity to insure vegetation growth and food for guanaco hunted by fisher-gatherer/hunter people living on the coast (Lavallée et al. 1999a, b). The increased fog production was certainly the origin of water resources in Quebrada. Conversely, when reservoir ages are low and upwelling is weak, no human settlements are found. Paleo-oceanographic reconstructions in equatorial upwelling and the Peru-Chile current give arguments supporting these observations (see references). Data obtained in Quebrada suggest lower sea surface temperatures during the early mid-Holocene period and agree with this hypothesis. Fish consumed by man at that period belong to a fauna colder than that observed today (Lavallée et al. 1999b), and the $\delta^{18}\text{O}$ values of shell carbonate that depend on sea surface salinity and temperature were also higher, indicating colder temperatures (salinity is assumed to be more or less constant) (Carré et al., forthcoming). Finally, Schrader and Snorkes (1991), Lyle et al. (1992), Farrell et al. (1995), and Marchant and Hebbeln (1999), notice higher organic carbon contents in marine early mid-Holocene sediment, related to an increased productivity as a result of the enhancement of upwelling strength. However, the doubling of reservoir age at around 7000–8000 cal BP appears much too important to result from an enhancement of upwelling alone because it would imply that upwelled waters had too deep an origin. Two hypothesis could be proposed: 1) the upwelled waters were older, or 2) the origin of waters was different, implying that Antarctic intermediate water ($\Delta^{14}\text{C} = -120\text{‰}$, pre-bomb value) were replaced during the upper Holocene by South Antarctic Mode Water ($\Delta^{14}\text{C} = -72\text{‰}$, pre-bomb value) that are upwelled today in the Peru-Chile current (Toggweiler et al. 1991). Whatever the cause of the change in reservoir age was, it corresponds to a major change in the circulation of the south Pacific Ocean around 7000–9000 cal BP. Our results agree with Van Beek et al. (2002) that show higher reservoir ages in the Southern Ocean at the beginning of the Holocene and with reconstruction of surface water pH and pCO₂ variations in the western equatorial Pacific Ocean,

which suggests an important CO₂ degassing as a result of the increased intensity of upwellings at that time (Palmer and Pearson 2003).

The enhancement of upwelling that is associated with strong trade winds and lower sea surface temperature suggests that the La Niña phenomenon would have been the prevailing situation during the early Holocene. This implies that El Niño events were less frequent and certainly less strong than during the upper Holocene and the present period, which is in good agreement with what we observe in sedimentological records at Quebrada de los Burros in coastal southern Peru.

ACKNOWLEDGEMENTS

Thanks are due to Martine Paterne for helpful discussions and Maurice Arnold for AMS measurements. Dr A J T Jull and an anonymous reviewer are acknowledged for suggestions in order to clarify the manuscript. Thanks are due to C Noury for sample preparations. This study was supported by the Franco-Peruvian archaeological project “Pérou-Sud” and the CONCHAS project (PNEDC, CNRS), LSCE contribution nr 1106.

REFERENCES

- Carré M, Bentaleb I, Fontugne M, Lavallée D. Forthcoming. Strong El Niño events during early Holocene: stable isotope evidence from Peruvian sea shell. *The Holocene*.
- Farrell JW, Pedersen TF, Calvert SE, Nielsen B. 1995. Glacial-interglacial changes in nutrient utilization in the equatorial Pacific ocean. *Nature* 377:514–7.
- Fontugne M, Usselman P, Lavallée D, Julien M, Hatté C. 1999. El Niño variability in the coastal desert of southern Peru during the mid-Holocene. *Quaternary Research* 52:171–9.
- Kennett DJ, Ingram BL, Southon J, Wise K. 2002. Differences in ¹⁴C age between stratigraphically associated charcoal and marine shell from archaic period site of kilometer 4, southern Peru: old wood or old water? *Radiocarbon* 44(1):53–8.
- Lavallée D, Julien M, Béarez P, Usselman P, Fontugne M, Bolaños A. 1999a. Pescadores-recolectores arcaicos del extremo-sur peruano. Excavaciones en la Quebrada de los Burros (Tacna, Perú): primeros resultados 1995–1997. *Bulletin Institut Français Etudes Andines* 28(1):13–52.
- Lavallée D, Béarez P, Chevalier A, Julien M, Usselman P, Fontugne M. 1999b. Paleoambiente y ocupación prehistórica del litoral extremo-sur del Perú: las ocupaciones del arcaico en la Quebrada de los Burros y alrededores (Tacna, Perú). In: Kaulicke P, editor. “El período arcaico en el Perú: hacia una definición de los orígenes.” *Boletín de Arqueología PUCP* 3:393–416.
- Lyle MW, Prah FG, Sparrow MA. 1992. Upwelling and productivity changes inferred from a temperature record in the central equatorial Pacific. *Nature* 355: 812–5.
- Marchant M, Hebbeln D. 1999. High-resolution planktic foraminiferal record of the last 13,300 years from the upwelling area off Chile. *Marine Geology* 161:115–28.
- Owen BD. 2002. Marine reservoir age estimates for the far south coast of Peru. *Radiocarbon* 44(3):701–8.
- Palmer MR, Pearson PN. 2003. A 23,000-year record of surface water pH and pCO₂ in the western equatorial Pacific Ocean. *Science* 300:480–2.
- Reimer PJ, McCormac FG. 2002. Marine radiocarbon reservoir corrections for the Mediterranean and Aegean Seas. *Radiocarbon* 44(1):159–66.
- Schader H, Sorknes R. 1991. Peruvian coastal upwelling: late Quaternary productivity changes revealed by diatoms. *Marine Geology* 97:233–49.
- Siani G, Paterne M, Arnold M, Bard E, Metivier B, Tisnérat N, Bassinot F. 2000. Radiocarbon reservoir ages in the Mediterranean Sea and Black Sea. *Radiocarbon* 42(2):271–80.
- Siani G, Paterne M, Michel E, Sulpizio R, Sbrana A, Arnold M, Haddad G. 2001. Mediterranean sea surface radiocarbon age changes since the last glacial maximum. *Science* 294:1917–20.
- Southon J, Kashgarian M, Fontugne M, Metivier B, Yim WWS. 2002. Marine reservoir corrections for the Indian Ocean and Southeast Asia. *Radiocarbon* 44(1): 167–80.
- Stuiver M, Polach H. 1977. Discussion: reporting of ¹⁴C data. *Radiocarbon* 19(3):355–63.
- Stuiver M, Reimer PJ, Bard E, Beck WJ, Burr GS, Hughen KA, Kromer B, McCormac G, van der Plicht J, Spurk M. 1998. INTCAL 98 radiocarbon age calibration, 24,000–0 cal BP. *Radiocarbon* 40(3):1041–83.
- Stuiver M, Braziunas TF. 1993. Modelling atmospheric ¹⁴C influences and ¹⁴C ages of marine samples to 10,000 BC. *Radiocarbon* 35(1):137–89.
- Tisnérat-Laborde N, Poupeau JJ, Tannau JF, Paterne M. 2001. Development of a semi-automated system for routine preparation of carbonate samples. *Radiocarbon* 43(2A):299–304.

- Toggweiler JR, Dixon K, Broecker WS. 1991. The Peru upwelling and the ventilation of the South Pacific thermocline. *Journal of Geophysical Research* 96(C11):20,467–97.
- Usselman P, Fontugne M, Lavallée D, Julien M, Hatté C. 1999. Estabilidad y ruptura dinámicas en el Holoceno de la costa surperuana/el Valle de la Quebrada de los Burros (Departamento de Tacna). *Bulletin Institute Française Etudes Andines* 28 (1): 1–11.
- Van Beek P, Reyss JL, Paterne M, Gersonde R, Van Der Loeff MR, Kuhn G. 2002. ²²⁶Ra in barite: absolute dating of Holocene southern sediments and reconstruction of reservoir ages. *Geology* 30(8):731–4.
- Vita-Finzi C, Roberts N. 1984. Selective leaching of shells for ¹⁴C dating. *Radiocarbon* 26(1):54–8.