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Quantitative estimation of Holocene surface salinity variation in the Black Sea using dinoflagellate cyst process length

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ABSTRACT

Reconstruction of salinity in the Holocene Black Sea has been an ongoing debate over the past four decades. Here we calibrate summer surface water salinity in the Black Sea, Sea of Azov and Caspian Sea with the process length of the dinoflagellate cyst *Lingulodinium machaerophorum*. We then apply this calibration to make a regional reconstruction of paleosalinity in the Black Sea, calculated by averaging out process length variation observed at four core sites from the Black Sea with high sedimentation rates and dated by multiple mollusk shell ages. Results show a very gradual change of salinity from ~14 ± 0.91 psu around 9.9 cal ka BP to a minimum ~12.3 ± 0.91 psu around 8.5 cal ka BP, reaching current salinities of ~17.1 ± 0.91 psu around 4.1 cal ka BP. The resolution of our sampling is about 250 years, and it fails to reveal a catastrophic salinization event at ~9.14 cal ka BP advocated by other researchers. The dinoflagellate cyst salinity-proxy does not record large Holocene salinity fluctuations, and after early Holocene freshening, it shows correspondence to the regional sea-level curve of Brückner et al. (2010) derived from Balabanov (2007).

1. Introduction

It has been suggested that during the Holocene, the Black Sea changed rapidly from a freshwater – brackish environment into higher salinity conditions during a catastrophic megaflood event around 7.5 cal ka BP, called 'Noah's flood' (Ryan et al., 1997). The age of this suggested megaflood event was later changed to 9.4 cal ka BP by Ryan et al. (2003). They converted their raw radiocarbon estimate of the timing of the flood (8.4 ^{14}C ka) to calendar years using a reservoir age of zero years. In this paper, we have recalibrated their raw age using a reservoir age of 300 years (Soulet et al., 2011; procedures explained in Table 1 and applied to all radiocarbon dates in this paper); with this revised calibration procedure, the date of the proposed megaflood event is reduced to ~9.14 cal ka BP. According to the hypothesis of Ryan and coworkers, the sudden input of saltwater at ~9.14 cal ka BP resulted in an abrupt increase of salinity and rapid rise of the water level from a depth of more than 100 m below sea level (Ryan and Pitman, 1998). Conflicting evidence was presented by Aksu et al. (2002a,b), Hiscott et al. (2002) and Mudie et al. (2001, 2002, 2004) who hypothesized persistent early Holocene outflow of brackish water from the Black Sea into the Marmara Sea before the

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Table 1

Radiocarbon ages with increasing depth in the composite stratigraphy at four core sites in the Black Sea, reported as uncalibrated conventional ^{14}C dates in yr BP (half-life of 5568 years; errors are 68.3% confidence limits) and calibrated calendar ages (cal yr BP) determined with Oxcal4.0 online software, Marine09.14c calibration curve. We use a reservoir age of 415 yr (Siani et al., 2000) for all raw dates younger than 7.1 ^{14}C ka. We use a reservoir age of 300 yr for all raw dates older than 8.4 ^{14}C ka in shelf cores MAR02-45, MAR05-04G and MAR05-13P, consistent with Soulet et al. (2011). 7.1 ^{14}C ka and 8.4 ^{14}C ka are, respectively, the times of euryhaline mollusc appearance and first influence of Mediterranean water identified by Ryan et al. (1997) and Ryan et al. (2003). For raw shell dates between 7.1 ^{14}C ka and 8.4 ^{14}C ka in shelf cores, we use linear interpolation to obtain an appropriate reservoir age between 300 yr and 415 yr. For our two deep-water sites, we use a reservoir age of 1000 yr prior to 7.5 ^{14}C ka and 415 yr for younger raw dates. Prior to 7.1–7.5 ^{14}C ka, the reservoir values are different for shelf sites and deep-water sites because of water-column stratification (Kwiecien et al., 2008). Laboratory numbers bear the prefix “TO” for IsoTrace Radiocarbon Laboratory, Accelerator Mass Spectrometry Facility, University of Toronto, the prefix “UCIAMS” for Radiocarbon Dating Laboratory, Université Laval, and the prefix “KIA” for Leibniz-Labor für Altersbestimmung und Isotopenforschung of the University of Kiel. Extrapolated ages on either side of unconformities α_1 and α_2 have error bars consistent with all combinations of ±errors of the two radiocarbon ages above and below that level.

Core	Depth (cm)	Composite depth (cm)	Water depth (m)	Dated material	^{14}C date (year BP)	Calendar age (cal yr BP)	Lab No./Reference
MAR 02-45T	0	0	69	Modern core top	415 ± 90	0	Reservoir age
MAR 02-45T	92	92	69	*Spisula subtruncata*	730 ± 50	365 ± 50	TO-11433
MAR 02-45P	33	143	69	*Spisula subtruncata*	730 ± 40	365 ± 45	TO-11435
MAR 02-45T	145	145	69	*Spisula subtruncata*	770 ± 50	395 ± 55	TO-11434
MAR 02-45P	158	268	69	*Mytilus edulis*	2400 ± 60	2025 ± 80	TO-11006
MAR 02-45P	160	270	69	Just above α_2	2425 ± 60	2050 ± 80	Extrapolation
MAR 02-45P	161	271	69	Just below α_2	5095 ± 25	5465 ± 55	Extrapolation
MAR 02-45P	174	284	69	*Mytilus galloprovincialis*	5115 ± 20	5480 ± 45	UCIAMS-85907
MAR 02-45P	220	330	69	*Mytilus edulis*	5190 ± 50	5535 ± 55	TO-11436
MAR 02-45P	302	412	69	*Mytilus galloprovincialis*	5900 ± 60	6310 ± 65	TO-11437
MAR 02-45P	406	516	69	*Monodacna pontica*	7560 ± 60	8055 ± 65	TO-11438
MAR 02-45P	495	605	69	*Truncatella subcylindrica*	8380 ± 70	9120 ± 95	TO-11142
MAR 02-45P	569	679	69	*Didacna ?praetrigonoides*	8570 ± 70	9335 ± 85	TO-11439
MAR 02-45P	639	749	69	*Didacna* spp.	8620 ± 70	9385 ± 75	TO-11440
MAR 02-45P	754	864	69	*Dreissena rostiformis*	8840 ± 70	9635 ± 100	TO-11441
MAR 02-45P	810	920	69	*Dreissena rostiformis*	9370 ± 70	10,335 ± 80	TO-11007
MAR 05-04G	0	0	75	Modern core top	415 ± 90	0	Reservoir age
MAR 05-04G	17	17	75	*Parvicardium exigum*	540 ± 50	155 ± 70	TO-13196
MAR 05-13P	16	46	75	Bivalve fragments	1380 ± 50	915 ± 60	TO-13198
MAR 05-13P	87	117	75	Bivalve fragments	2230 ± 60	1820 ± 75	TO-12906
MAR 05-04G	137	137	75	*Mytilus galloprovincialis*	2600 ± 60	2255 ± 80	TO-13197
MAR 05-13P	253	283	75	Bivalve fragments	3940 ± 60	3920 ± 90	TO-12907
MAR 05-13P	384	414	75	Bivalve fragments	4170 ± 60	4235 ± 90	TO-12908
MAR 05-13P	441	471	75	*Mytilus galloprovincialis*	4770 ± 70	5035 ± 110	TO-12909
MAR 05-13P	504	534	75	*Mytilus galloprovincialis*	5960 ± 80	6375 ± 85	TO-12910
MAR 05-13P	620	650	75	*Mytilus galloprovincialis*	6370 ± 90	6835 ± 115	TO-12911
MAR 05-13P	647	677	75	Bivalve fragments	7020 ± 100	7505 ± 90	TO-12912
MAR 05-13P	659	689	75	Just above alpha1	7310 ± 135	7805 ± 125	Extrapolation
MAR 05-13P	660	690	75	Just below alpha1	8280 ± 95	8940 ± 100	Extrapolation
MAR 05-13P	696	726	75	*Turricaspia spica*	8740 ± 70	9515 ± 75	TO-12834
MAR 05-13P	784	814	75	Bivalve fragments	9870 ± 90	10,915 ± 140	TO-12913
GeoB7625-2	46	46	1242	*Mytilus galloprovincialis* in GeoB7622-2	1170 ± 35	705 ± 35	KIA-25671
GeoB7625-2	158	158	1242	*Mytilus galloprovincialis* in GeoB7622-2	2095 ± 30	1660 ± 50	KIA-25749
GeoB7625-2	293	293	1242	*Mytilus galloprovincialis* in GeoB7622-2	2385 ± 35	2005 ± 55	KIA-25672
GeoB7625-2	388	388	1242	*Mytilus galloprovincialis* in GeoB7622-2	3080 ± 35	2840 ± 50	KIA-25751
GeoB7625-2	466	466	1242	Santorini ash		3331 ± 10	Friedrich et al., 2006
GeoB7625-2	538	538	1242	*Mytilus galloprovincialis* in GeoB7622-2	4605 ± 55	4805 ± 80	KIA-25674
GeoB7625-2	578	578	1242	organic matter in GeoB7622-2	5715 ± 25	6120 ± 50	KIA-19273
GeoB7625-2	614	614	1242	*Mytilus galloprovincialis* in GeoB7622-2	6590 ± 70	7090 ± 85	KIA-25675
GeoB7625-2	624	624	1242	*Mytilus galloprovincialis* in GeoB7622-2	7625 ± 55	7515 ± 50	KIA-25753
GeoB7625-2	639.5	639.5	1242	Gastropod in MD04-2760	8505 ± 45	8375 ± 50	KIA-26698
BC53	28.5	28.5	2153	End of transition sapropel	1635 ± 60	1180 ± 65	Jones and Gagnon, 1994
BC53	31	31	2153	First invasion of the coccolith *Emiliania huxleyi*	2720 ± 160	2430 ± 200	Jones and Gagnon, 1994

level of the Marmara Sea and the world ocean reached the Bosphorus sill depth. This one-way outflow was followed, after an initial short-lived pulse of saline inflow at ~9.14 cal ka BP, by two-way flow and progressive, gradual filling of the Black Sea after ~7.5 ^{14}C ka BP (here calibrated by us to ~8.0 cal ka BP) when the Bosphorus sill was sufficiently inundated that water could flow unimpeded in both directions (Mudie et al., 2007; Hiscott et al., 2007a,b). Marret et al. (2009), using the same Black Sea core as Hiscott et al. (2007b), proposed a gradual two-step filling of the Black Sea during the Holocene. Other paleosalinity studies have measured interstitial sediment water chlorinity and δ^{18}O values and concluded that freshwater (~1 psu) filled the Black Sea to at least −350 m until ca 9.0 cal ka BP (Soulet et al., 2010), while benthic ostracod δ^{18}O values were used by Bahr et al. (2006) and Vidal et al. (2010) to record apparent decreases or increases in salinity following disconnection of the Black and Marmara seas during the Lateglacial – Holocene period. van der Meer et al. (2008) determined that alkenones show a freshening of the surface Black Sea water during the past 3000 years.

Here we tackle the problem of conflicting interpretations of the Holocene Black Sea paleosalinity record by investigating four AMS-dated sediment records of annual sea surface salinity (SSS) using changes in the process length of a dinoflagellate cyst *Lingulodinium machaerophorum* (Deflandre et Cookson 1955) Wall 1967 that are quantitatively calibrated to modern regional surface water conditions over the salinity range of 12.2–18.5 psu. Process length of *Lingulodinium machaerophorum*, the cyst of the autotrophic dinoflagellate *Lingulodinium polyedrum* (Stein 1883) Dodge 1989, was initially qualitatively related to presumed salinity changes in the Black Sea by Wall et al. (1973) and subsequently used