



Universidad
de Chile

Evelyn Valeria Bocaz Escobar <ebocaz@u.uchile.cl>

Solicitud convalidación Práctica Profesional

Evelyn Valeria Bocaz Escobar <ebocaz@u.uchile.cl>
Borrador a: Carola Flores <carolaflowers@gmail.com>

28 de mayo de 2019, 15:44

El lun., 13 may. 2019 a las 16:44, Carola Flores (<carolaflowers@gmail.com>) escribió:

Estimada Evelyn Bocaz

Adjunto documentos para solicitar convalidación de práctica profesional y así continuar con el proceso de memoria y titulación.

Los documentos son los siguientes:

1. carta de investigador responsable del proyecto donde realicé actividades a convalidar.
2. informe de los resultados de esas actividades.
3. publicación que incluye parte de los resultados de las actividades realizadas
4. CV

Quedo atenta a la confirmación de la recepción de los documentos.

Atte

Carola Flores

Carola Flores Fernández, PhD, Arqueología
Centro de Estudios Avanzados en Zonas Áridas (CEAZA)
<http://www.ceaza.cl>

Santiago, 13 de mayo de 2019

Dr. Ennio Vivaldi
Rector
Universidad de Chile

Estimado Sr. Rector,

Por medio de la presente, certifico que entre 2015 y 2017 la Dra. Carola Flores realizó actividades dentro del proyecto Fondecyt 1151203 "Trayectoria histórica, cambios ambientales y eventos catastróficos durante el Período Arcaico en la costa de Taltal, norte de Chile", las cuales cumplen con los requisitos académicos para ser convalidadas como Práctica Profesional.

Las actividades de la Dra. Flores estuvieron vinculadas con la selección y toma de muestras de conchas arqueológicas de *Fisurrella máxima* para análisis isotópico de Oxígeno 18 y Carbono 13, así como con el análisis e interpretación de resultados, todo lo anterior con el objeto de reconstruir las condiciones paleoambientales y paleoceanográficas de la zona de Taltal durante el Holoceno.

Las actividades tuvieron una duración mayor a 360 horas totales y constituyeron relevantes aportes científicos, parte de los cuales se encuentran ya publicados.

Sin otro particular, saluda atentamente,



Diego Salazar Sutil

Profesor Asociado

Departamento de Antropología - Universidad de Chile
Investigador Responsable Proyecto Fondecyt 1151203

CURRICULUM VITAE

Carola Flores Fernández

Investigadora Postdoctoral

Centro de Estudios Avanzado en Zonas Áridas (CEAZA), Ossandón 877, Coquimbo, Código Postal 1781681, +56 9 79517578
carolaflowers@gmail.com

GRADOS UNIVERSITARIO:

2005 Licenciada en Antropología con mención en Arqueología, Universidad de Chile.
2008 Maestría en Arqueología, Universidad de California, Santa Bárbara. USA
2014 Doctorado en Arqueología, Universidad de California, Santa Bárbara. USA
2017-2020 Investigadora postdoctoral, CEAZA, Chile

EXPERIENCIA EN TERRENO

Arqueología

- Procesos y orígenes del poblamiento marítimo de los canales Patagónicos: Chiloé y el núcleo Septentrional. Chile. FONDECYT 1020616. Prospecciones, columnas de muestreo y excavación arqueológica. Técnico de terreno y laboratorio. Investigador Responsable Carlos Ocampo (2002-2005).
- Ocupaciones Lacustres Paleolíticas y Mesolíticas alrededor del Lago Federsee. Alemania. Excavación arqueológica. Técnico de terreno. Investigador Responsable Michael Jochim. Universidad de California, Santa Bárbara, EEUU (2009).
- Evidencia Arqueológica de un posible sitio ceremonial de cazadores recolectores. Acapetahua, Chiapas, México. National Geographic y U.C. Mexus. Excavación arqueológica. Técnico de terreno. Investigador Responsable Barbara Voorhies, Universidad de California, Santa Barbara, EEUU (2009).
- Impacto Humano en Ecosistemas Intermareales Pasados en la isla de Santa Cruz, California. Una aproximación multidisciplinaria. Investigadora doctoral. Tutor: Michael Glassow, Universidad de California, Santa Bárbara, EEUU (2009-2014).
- Cazadores-recolectores, pescadores y mineros del período arcaico en la costa de Taltal, norte de Chile. FONDECYT 1110196. Excavación, prospección y análisis de materiales. Investigadora colaboradora. Investigador Responsable Diego Salazar, Universidad de Chile (2011-2014).
- Trayectoria histórica, cambios ambientales y eventos catastróficos durante el período Arcaico en la costa de Taltal, Norte de Chile. FONDECYT 1151203. Excavación, prospección y análisis de materiales. Co-Investigadora. Investigador Responsable Diego Salazar, Universidad de Chile (2015-2018).

EXPERIENCIA DE LABORATORIO

Arqueología

- Análisis arqueo-malacológicos de sitios arqueológicos del Seno de Reloncaví, Chiloé, Concepción, La Serena y Copiapó. Chile. Proyectos de Investigación y Estudios de impacto ambiental (2005-2010).
- Análisis arqueo-malacológico. Sitios de cazadores recolectores costeros del Holoceno Tardío, Isla de Santa Cruz, California, EEUU. Tesis doctoral. Tutor: Michael Glassow, Universidad de California, Santa Barbara, EEUU (2009-2014).
- Preparación de conchas arqueológicas *Choromytilus californianus* para análisis isotópicos ($\delta^{18}\text{O}$ - $\delta^{13}\text{C}$) y elaboración de secuencias locales de paleotemperatura superficial del mar durante el Holoceno Tardío (2200-500 cal A.P.) en la costa de la Isla de Santa Cruz, California (2012-2014).
- Análisis de artefactos de anzuelos en conchas de *Choromytilus chorus* y desechos de manufactura provenientes de sitios arqueológicos del Holoceno Medio de la costa de Taltal, Región de Antofagasta, Chile (2014-2015).

- Preparación de conchas arqueológicas y modernas de *Fisurella maxima* para análisis isotópicos (δO^{18} - $\delta^{13}C$) y elaboración de secuencias locales de paleotemperatura superficial del mar del Holoceno en la costa de Taltal, Región de Antofagasta, Chile (2015-2018).
- Morfometría Geométrica en anzuelos de concha de la costa del Desierto de Atacama.

CONGRESOS Y CONFERENCIAS

2014

- *Importance of Past Small-Scale Ecological and Oceanographic variability for Studies about Human Exploitation of Ancient Intertidal Habitats An example from Santa Cruz Island, California.* Carola Flores. XII International Conference of Archaeozoology, XII, San Rafael, Argentina. Septiembre 21-26.

2015

- *Effect of Past Ecological and Oceanographic Variability on Shellfish harvesting and Suitability of Coastal Locations. A Case Study from two Late Holocene sites (2200-500 cal B.P.), Santa Cruz Island, California.* Carola Flores. SAA (Sociedad de Arqueología Americana) 80 Reunión anual, San Francisco, California, EEUU. Abril 15-19.
- *Production of Fishing Artifacts on Mussel Shells (*Choromytilus chorus*) during the Middle Holocene on the coast of Taltal, Atacama Desert, Chile.* Valentina Figueroa, Carola Flores, Diego Salazar. SAA (Sociedad de Arqueología Americana) 80 Reunión anual, San Francisco, California, EEUU. Abril 15-19.

2016

- *Early Coastal Occupations in Taltal, Southern Atacama Desert, Chile.* Carola Flores, Diego Salazar, Laura Olguín, Gabriel Vargas and Camila Arenas. SAA (Sociedad de Arqueología Americana) 81 Reunión anual, Orlando, Florida, EEUU. Abril 6-10.
- *Date and context of early mussel shell fishhooks (*Choromytilus chorus*) from the southern coast of the Atacama Desert, Taltal, Chile.* Carola Flores, Laura Olguín, Sandra Rebolledo, Diego Salazar. SAA (Sociedad de Arqueología Americana) 81 Reunión anual, Orlando, Florida, EEUU. Abril 6-10.
- *Estrategias de subsistencia en cazadores, recolectores, pescadores y miners del arcaico en la costa del Desierto de Atacama, Taltal, Chile (12.000 – 1.500 cal. AP).* Laura Olguín, Carola Flores, Valentina Duran, Javiera Guardia, Douglas Jackson, Isaac Peña-Villalobos, Sandra Rebolledo, Consuelo Sandoval, Claudia Talep y Jimena Torres. XIX Congreso nacional de Arqueología Argentina. Tucumán. Agosto 8-12.
- *Past sea surface temperature and human intertidal gathering during the Holocene on SantaCruz Island: Evidence from Oxygen isotope (δO^{18}) and archaeomalacological data.* Carola Flores, Amy E. Gusick, Heather Thakar. 9th California Islands Symposium. Ventura, California. October 3-7.

2017

- *Transitions in ancient fishing communi_es, Atacama Desert (Chile).
Fishing tools on C. chorus mussel shell (8000 to 4500 years BP).* Carola Flores, Verónica Alcalde, Pablo Oyanadel-Urbina, Marcelo Rivadeneira, Diego Salazar. EAA, Maastricht, Netherlands. August 30-Septiembre 3.
- *Temperatura superficial del mar (TSM) en la costa Norte de Chile (Taltal, 25° Lat. S). Registro de $\delta^{18}O$ en conchas de Fisurella máxima y sus implicancias para los asentamientos humanos durante el Holoceno Temprano (10.500-9.500 cal B.P.).* Carola Flores, Bernardo Broitman, Diego Salazar, Eugenia Gayó. Taller de Isótopos Estables, San Rafael, Mendoza. Octubre-Nov.
- *Análisis isotópicos aplicados al estudio de modos de vida de grupos pescadores durante la prehistoria. Taltal (25 Lat S), Chile.* Carola Flores, Pedro Andrade, Jimena Torres. Primer Simposio Nacional de Isótopos Estables. Julio 2017. Santiago. Universidad Andrés Bello.

2018

- *Shell fishhooks on C. chorus mussel shell (7500 to 4500 years BP) from the Atacama Desert Coast (Chile).* Carola Flores, Verónica Alcande, Laura Olguín, Jimena Torres, Diego Salazar. SAA (Sociedad de Arqueología Americana) 83 Reunión anual. Washington, D.C. USA. Abril 11-15.
- *Nearshore paleoceanographic conditions and human adaptation on the coast of the Atacama Desert (Taltal, 25°S) during the Early and Middle Holocene. Oxygen Isotope Analyses ($\delta^{18}O$) on Fissurella maxima shells.* Carola Flores, Laura Olguín, Sandra Rebolledo, Eugenia Gayó, Diego Salazar, Bernardo Broitman. 11th International Conference on the Applications of Stable Isotope Techniques to Ecological Studies (IsoEcol 2018). Viña del Mar. Chile. Julio 30- Agosto 3.
- "10.500 años (12.000 – 1.500 A.P) de uso y consumo de invertebrados marinos provenientes de conchales de la costa arica del desierto de Atacama, Chile". Javiera Guardia, Laura Olguín, Carola Flores, Bernardo Broitman. IV Encuentro Latinoamericano de ArqueoZoolología (ELAZ). Río Gallegos, Argentina, 21-23 Noviembre.
- "Morfometría geométrica en anzuelos de concha de Choromytilus chorus de la costa Paposito-Taltal, Norte de Chile". Verónica Alcande y Carola Flores. XXI Congreso Nacional de Arqueología Chilena. Santiago, Chile, 3-7 Diciembre.

2019

- "Nearshore paleoceanographic conditions and human adaptation on the coast of the Atacama Desert (Chile, 25°S) during the Early and Middle Holocene." Carola Flores, Sandra Rebolledo, Jimena Torres, Diego Salazar, Bernardo R. Broitman. En sesión Palaeoeconomic and environmental reconstructions in Island and Coastal archaeology. 84th Annual Meeting of the Society for American Archaeology, 10-14 Abril, Albuquerque, USA.
- "Swordfish hunting as prestige signaling within Middle Holocene fishing communities of the Atacama Desert Coast?" Carola Flores y Diego Salazar. En session Human Behavioral Ecology at the Coastal Margins. Global Perspectives on Coastal & Maritime Adaptations. 84th Annual Meeting of the Society for American Archaeology, 10-14 Abril, Albuquerque, USA.

BECAS Y CONCURSOS**2015**

- Trayectoria histórica, cambios ambientales y eventos catastróficos durante el Período Arcaico en la costa de Taltal, norte de Chile. Fondo Nacional de Ciencia y Tecnología (FONDECYT) #1151203- Chile (2015-2018). Co-Investigadora. Investigador Principal, Diego Salazar (Universidad de Chile).
- Historia Oral del Pueblo del Romero: Origen del Pueblo y su Gente en la Retina de los Abuelos. Proyecto del Consejo Nacional de la Cultura y las Artes (FONDART) 71726. La Serena, Chile. Investigadora Responsable.

2017

- Sistema de Producción de Artefactos de Pesca en Concha de *Choromytilus chorus* durante el Arcaico de la Costa Arica Chilena (Taltal). FONDECYT Postdoctoral #3170913 (2017-2019). Investigadora Responsable.

PUBLICACIONES

Correa I. & **C. Flores, (2005)**. Pintura corporal Selknam y su carácter iconográfico. *Revista Werkén*. Vol 7: 21-37.

Flores C. & N. Lira, **(2006)**. Aspectos comunes para sitios de cazadores recolectores costeros en los canales patagónicos septentrionales. *Boletín de la Sociedad Chilena de Arqueología*. Vol 39: 103-112.

Flores C., (2007). Estrategias de aprovechamiento de la diversidad ecológica del intermareal prehistórico: conchales arqueológicos del Seno de Reloncaví, X región, Chile. *Arqueología de Fuego-Patagonia. Levantando piedras, desenterrando huesos... y develando arcanos* Ediciones CEQUA. Pp 33-38 ISBN 978-956-8692-00-1

Flores C., (2009). Shell middens in a Pacific island village. Baraulu, Roviana Lagoon, Western Solomon Islands. *SAA archaeological record. The magazine of the Society for American Archaeology*, Vol 9, nº 5:19-21.

Flores C. F., B. R. Broitman, and P. Rivas, (2010). Cambios en las estrategias de subsistencia del intermareal prehistórico: cazadores recolectores pre-cerámicos y cerámicos del Seno de Reloncaví, Chile. *Comparative Perspectives on the Archaeology of Coastal South America*. Robyn Cutright, Enrique López-Hurtado y Alexander Martin editores. Publicaciones Latinoamericanas, Universidad de Pittsburgh. Pp: 63-75. ISBN 978-1-877812-88-0

Flores C. & I. Correa, (2011). Explotación de ambientes costeros, intensificación de recursos y transformaciones culturales en la transición Holoceno Medio a Holoceno Tardío en la costa de los canales Patagónicos Septentrionales, Chile. *Actas del XVII Congreso Nacional de Arqueología Argentina*. Volumen I, Capítulo 6: 321-326. ISBN: 978-987-9126-83-7

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Mengozzi F., R. Contreras, P. Andrade, X. Power, **C. Flores**, D. Salazar, G. Bravo, J. Urrea, R. Fernandes, C. Hamann. Reconstrucción de un contexto funerario disturbado. Artefactos y ecofactos del sitio El Gaucho (229 cal AP), costa Arreica del Norte de Chile, (2016). *Revista Taltalia*, 9:7-25.

Jerardino A., P. Faulkner & **C. Flores**, (2017). Current methodological issues in archaeomalacological studies. *Quaternary International*, 427, Part A:1-4.

Flores C., (2017). Importance of small-scale paleo-oceanographic conditions to interpret changes in size of California mussel (*Mytilus californianus*). Late Holocene, Santa Cruz Island, California. *Quaternary International*, 427, Part A:137-150.

Blanco, J., I. Correa, **C. Flores**, (2017). La extracción prehispánica de recursos minerales en el internodo Quillagua-Costa, Desierto de Atacama. *Estudios Atacameños*, En Prensa. http://www.scielo.cl/scielo.php?pid=S0718-10432017005000003&script=sci_abstract

Salazar, D., C. Arenas, P. Andrade, L. Olguín, J. Torres, **C. Flores**, G. Vargas, S. Rebolledo, C. Borie, C. Sandoval, C. Silva, A. Delgado, N. Lira, C. Robles, (2018). From the use of space to territorialisation during the Pleistocene-Holocene transition in Taltal, coastal Atacama Desert, Chile. *Quaternary International*, 473:225-241.

Flores C., Broitman, B.R., Salazar, D., Gayo, E., (2018). $\delta^{18}\text{O}$ of *Fissurella maxima* as a proxy for reconstructing Early Holocene sea surface temperatures in the coastal Atacama desert (25°S), Palaeogeography, Palaeoclimatology, Palaeoecology, 499, 22-34.

Daniel Sznycer, Dimitris Xygalatas, Elizabeth Agey, Sarah Alami, Xiao-FenAn, Kristina I. Ananyeva, Quentin D. Atkinson, Bernardo R. Broitman, Thomas J. Conte, **Carola Flores**, Shintaro Fukushima, Hidefumi Hitokoto, Alexander N. Kharitonov, Charity N. Onyishi, Ike E. Onyishi, Pedro P. Romero, Joshua M. Schrock, J. Josh Snodgrass, Lawrence S. Sugiyama, Kosuke Takemura, Cathryn Townsend, Jin-Ying Zhuang, C. Athena Aktipis, Lee Cronk, Leda Cosmides, John Tooby, (2018). Cross-cultural invariances in the architecture of shame. *Proceedings of the National Academy of Sciences*, 115 (33): 8322-8327.

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Gayo, E.M., Campbell, R., McRostie, V., **Flores, C.**, Maldonado, A., Uribe-Rodriguez, M., Moreno, P.I., Santoro, C.M., Christie, D. A., Muñoz, A.A., Gallardo, L. (2019). Geohistorical records of the Anthropocene in Chile. Aceptada en *Elementa: Science of the Anthropocene*.

Salazar, D., **Flores, C.**, Borie, C., Olguín, L., Rebolledo, S., Escobar, M., Cifuentes, A. (2019). Economic organization and social dynamics of Middle-Holocene hunter-gatherer-fisher communities in the coast of the Atacama Desert (Taltal, northern Chile). Aceptado. En

Maritime Communities of the Ancient Andes, Editores Gabriel Prieto y Daniel Sandweiss. Capítulo 3.

Flores, C., Alcalde, V. (2019). Variabilidad morfológica de anzuelos de concha de *Choromytilus chorus* (8500-4500 años AP) en la costa de Paposo-Taltal, Norte de Chile. Manuscrito en revisión, Revista Chungara, Universidad de Tarapacá.

Castelleti, J., Reyes, O., Trejo, V., **Flores, C.**, Villaroel, M. (2019). Choluto, o la voz de la construcción del paisaje fúnebre costero arreico, durante la transición Arcaico-formativo en Taltal. Manuscrito enviado para revisión, Revista Taltalia, Museo Arqueológico Augusto Capdeville.

Departamento de Antropología
Facultad de Ciencias Sociales
Universidad de Chile

Condiciones paleoceanográficas de la zona de Taltal durante el Período Arcaico

Alumna: Carola Flores
Profesor Supervisor: Diego Salazar

Introducción

El objetivo de las actividades realizada fue reconstruir las condiciones paleoambientales y paleoceanográficas de la zona de Taltal durante el Período Arcaico.

Basado en la fuerte relación entre temperatura superficial del mar (TSM) y condiciones de productividad y abundancia de recursos de la franja litoral (Broitman et al. 2001; Valdivia et al. 2013), variaciones identificadas en TSM a lo largo del tiempo pueden ser utilizadas como proxy para caracterizar las condiciones ambientales generales experimentadas por los grupos humanos que habitaron la costa durante la prehistoria y evaluar posibles correlaciones con variabilidad observada en el registro arqueológico.

Materiales y métodos

De esta forma, con el objetivo de reconstruir la variabilidad oceanográfica (TSM promedio) durante el Arcaico de la costa de Taltal y proponer condiciones climáticas generales para la zona, se realizaron análisis isotópicos (δO^{18} y δC^{13}) sobre conchas de molusco de la especie *Fissurella máxima*. Estas conchas fueron obtenidas de siete sitios arqueológicos (Tabla 1) ubicados al norte, centro y sur del área de estudio. Las conchas analizadas fueron fechadas directamente en el laboratorio de Northern Arizona University (Amino Acid Geochronology Lab) y luego calibradas (Calib 7.1, SHCal 13 curve, efecto reservorio 226 ± 98 de Ortlieb et al. 2011) (Archivo Excel "Detalle Fechas Conchas FMaxima").

Se seleccionó un total de 49 conchas de *F. maxima*, de las cuales se obtuvieron 383 muestras de carbonato. Para el período Arcaico I, se analizaron ocho conchas (71 muestras) con fechas entre 11.500 y 10.000 años antes del presente (AP). Para el Arcaico III, Momento 1, se analizaron cuatro conchas (32 muestras) con fechas entre 7.600 y 6.900 AP y para el período Arcaico III, Momento 2, se analizaron seis conchas (48 muestras) con fechas entre 5.800 y 5.900 AP. Ocho conchas (60 muestras) con fechas entre 4.900 y 4.500 AP fueron analizadas para el Arcaico IV, dos conchas (12 muestras) con fechas entre 4.500 y 3.600 AP fueron analizadas para el Arcaico V, seis conchas (48 muestras) con fechas entre 2.800 y 1.600 AP fueron analizadas para el Arcaico VI y finalmente 6 conchas (48 muestras) con fechas entre 1.100 y 600 años AP fueron analizadas para el período Intermedio Tardío y Tardío (Tabla 1). Para el Arcaico II, a pesar de que se recolectaron muestras de conchas de depósitos asignados a este período, los análisis de radiocarbono

realizados en ellas dieron fechas más tardías correspondientes al Arcaico III. Junto con la muestra arqueológica se analizaron 8 conchas modernas (64 muestras).

Tabla 1. Número de conchas de *F. maxima* analizadas por sitios y períodos

	Arcaico I 11500- 10000 AP	Arcaico III M1 7600-6900 AP	Arcaico III M2 5800-5900 AP	Arcaico IV 4900- 4500 AP	Arcaico V 4500- 3600 AP	Arcaico VI 2800- 1600 AP	PIT/PT 1100- 600 AP	Modernas 2015- 2016	Total por sitio
Zapatero			6	1			4		11
Alero PN9	4			4	1	3			12
Alero Bandurrias 3							1		1
Alero 224A	5			2	1	3	1		12
Paso Malo Arcaico				1					1
Morro Colorado		4							4
Taltal								4	4
Paposo								4	4
Total por período	9	4	6	8	2	6	6	8	49

Los valores de δO^{18} obtenidos de estas conchas fueron convertidos a valores de temperatura superficial del mar (TSM) siguiendo la metodología explicitada en Flores et al. 2018.

Los valores promedios de TSM de cada concha permitieron reconstruir la variabilidad paleoceanográfica a lo largo de la secuencia ocupacional completa de la zona de Taltal, desde los 11.400 a 630 años AP. Asimismo, las conchas modernas permitieron comparar valores pasados de TSM con parámetros modernos (Flores et al. 2018).

Resultados

Las conchas de *F. máxima* analizadas isotópicamente se distribuyen cronológicamente en 6 grupos generales abarcando todos los períodos Arcaicos definidos por Salazar et al. (2015), a excepción del período Arcaico II (Figura 1).

Figura 1. Distribución cronológica de las conchas de *F. maxima* analizadas para isótopos.

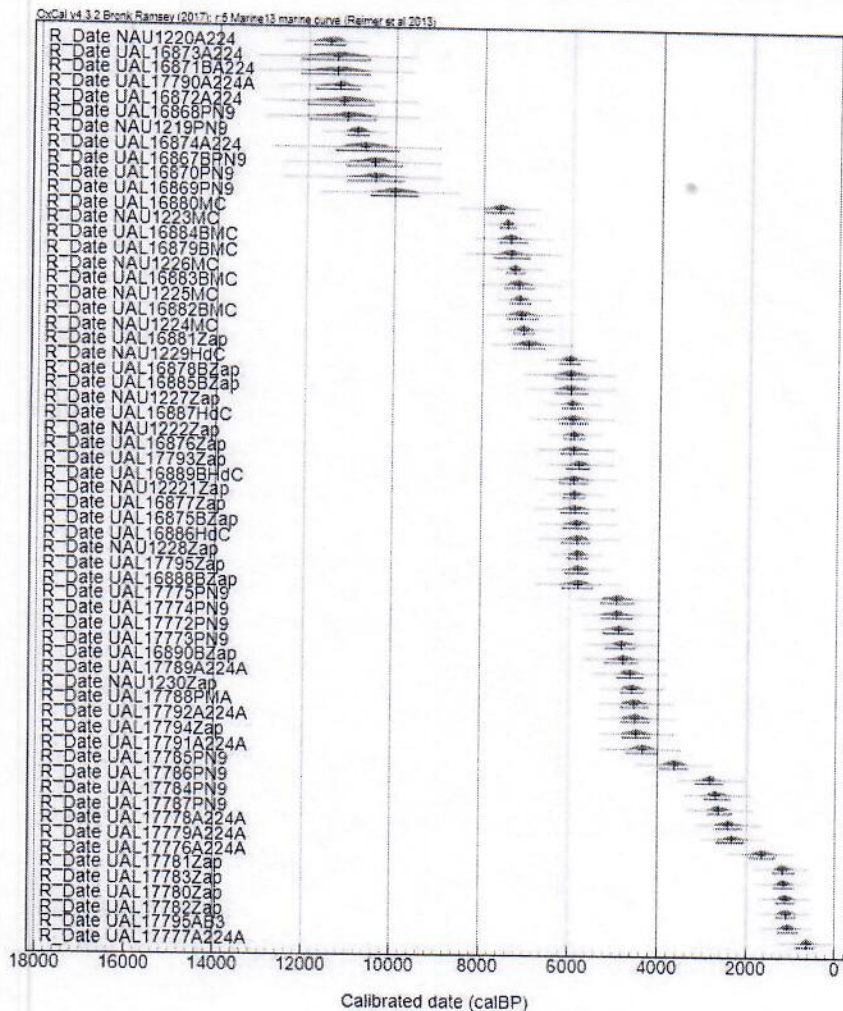


Figura 2 muestra en su parte superior valores promedios de TSM (SST su sigla en inglés) a partir de valores de δO^{18} y en su parte inferior valores promedios de δC^{13} como proxy para intensidad de la surgencia. Estos resultados muestran que durante el Holoceno Temprano (Arcaico I) la TSM fue más fría que durante el resto del Holoceno. Posterior a los 8.000 años AP (Arcaico III) la TSM es considerablemente más cálida, enfriándose luego alrededor de los 6.000 años AP y manteniéndose en estas temperaturas hasta alrededor de los 3.000

años AP (Arcaico VI), cuando comienza a aumentar levemente la TSM hasta llegar a los valores presentes.

En relación a los valores promedios de δC^{13} , el patrón no es tan claro. Valores negativos o bajo la línea de valor 0 (Figura 1) están relacionados con momentos de surgencias más intensa, y valores positivos o sobre la línea de valor 0 están relacionados con momentos de surgencia más débil. Resultados presentes en Figura 1 y Tabla 2 muestran que los momentos de surgencia más intensa corresponden al Holoceno Temprano y el presente. Luego, posterior a los 8.000 años AP la intensidad disminuye considerablemente, aumentando levemente entre los 6.000 y 4.000 años AP. Posterior a estos momentos y hasta los 600 años AP se podría sugerir una tendencia hacia momentos de surgencia cada vez más débil y a su vez más variable.

Figura 2. Valores promedios de δO^{18} como proxy de TSM (SST su sigla en inglés) y valores promedios de δC^{13} como proxy para intensidad de surgencia.

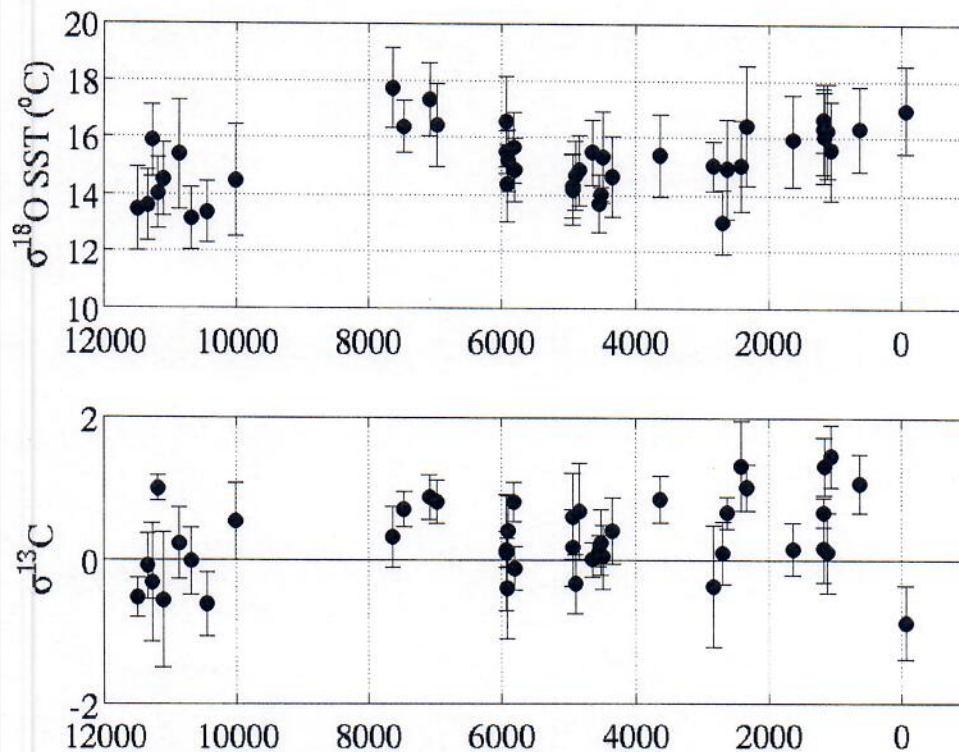


Tabla 2. Promedios de TSM (°C) por sitios y períodos

	Arcaico I 11500- 10000 AP	Arcaico III M1 7600-6900 AP	Arcaico III M2 5800-5900 AP	Arcaico IV 4900- 4500 AP	Arcaico V 4500- 3600 AP	Arcaico VI 2800- 1600 AP	PIT/PT 1100- 600 AP	Modernas 2015-2016	Total por sitio
Zapatero			15,36	15,32			16,32		15,71
Alero PN9	14,44			14,51	15,39	14,33			14,52
Alero Bandurrias 3							15,58		15,58
Alero 224A	14,02			15,01	14,65	15,80	16,33		14,89
Paso Malo Arcaico				13,39					13,39
Morro Colorado		16,97							16,97
Taltal								16,87	16,87
Paposo								17,12	17,12
Total por período	14,21	16,97	15,36	14,61	15,15	15,07	17,00	16,20	

Tabla 3. Promedios de δC^{13} por sitios y períodos

	Arcaico I 11500- 10000 AP	Arcaico III M1 7600-6900 AP	Arcaico III M2 5800-5900 AP	Arcaico IV 4900- 4500 AP	Arcaico V 4500- 3600 AP	Arcaico VI 2800- 1600 AP	PIT/PT 1100- 600 AP	Moderna s 2015- 2016	Total por sitio
Zapatero			0,16	0,05			0,57		0,30
Alero PN9	-0,10			0,29	0,86	0,14			0,17

Alero Bandurrias 3							1,47		1,47
Alero 224^a	-0,01			0,07	0,42	0,84	1,09		0,36
Paso Malo Arcaico				0,13					0,13
Morro Colorado		0,69							0,69
Paposo								-1,03	-1,03
Taltal								-0,72	-0,72
Total por período	-0,05	0,69	0,16	0,19	0,71	0,49	0,81	-0,87	

Conclusión

Existen variaciones importantes tanto en la TSM como en la intensidad de la surgencia a lo largo del Holoceno en la zona de Taltal que pueden haber influido en la disponibilidad de recursos costeros, especialmente algas, peces y moluscos (Broitman et al. 2001; Valdivia et al. 2013). Junto con esto, cambios a través del tiempo de la TSM e intensidad de surgencia puede haber afectado también la intensidad de la nubosidad costera o camanchaca, directamente relacionada con la humedad ambiental disponible y consecuentemente con la abundancia y reproducción de la vegetación de lomas (Cereceda et al., 2008; Garreaud et al., 2008; Rundel et al., 1991). Se proponen condiciones ambientales generales para la zona de Taltal con intensa camanchaca y alta productividad marina para el Holoceno Temprano. Esto disminuye drásticamente al inicio del Holoceno Medio, destacando la posibilidad de que aguas más cálidas cercanas a la costa hayan implicado la presencia o mayor abundancia de especies marinas previamente no utilizadas o subutilizadas y condiciones más áridas en el borde costero terrestre. Hacia el fin del Holoceno Medio las condiciones vuelven a ser más óptimas con mayor intensidad de camanchaca y productividad marina. Durante el Holoceno Tardío se presentan nuevamente condiciones paleoceanográficas más cálidas y menos productivas que podrían haber implicado una disminución en la camanchaca y humedad litoral terrestre.

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$\delta^{18}\text{O}$ of *Fissurella maxima* as a proxy for reconstructing Early Holocene sea surface temperatures in the coastal Atacama desert (25°S)

Carola Flores^{a,*}, Eugenia M. Gayo^b, Diego Salazar^c, Bernardo R. Broitman^a

^a Centro de Estudios Avanzados en Zonas Áridas (CEAZA), Facultad de Ciencias del Mar, Universidad Católica del Norte, Ossandón 877, Coquimbo, Chile

^b Departamento de Oceanografía, Universidad de Concepción, Centro de Ciencia del Clima y la Resiliencia (CR2), Barrio Universitario s/n, Concepción, Chile

^c Departamento de Antropología, Universidad de Chile, Ignacio Carrera Pinto 1045, Santiago, Chile

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ABSTRACT

Fissurella maxima is a keyhole limpet that is abundant and well preserved in archaeological shell midden sites along the coast of Chile, making it an appropriate species to use for reconstructions of past sea surface temperature (SST). In the present study we evaluate the potential of *F. maxima* shells as a proxy of SST by analysing $\delta^{18}\text{O}$ of modern shells collected alive from the Atacama desert (area of Taltal, 25°S) and archaeological shells from two Early Holocene rockshelter sites: 224A and Paposo Norte 9. Reconstructed SST from modern *F. maxima* shells were related to SST obtained from in situ thermometers, supporting the use of this mollusc species as a paleotemperature archive. Mean SST reconstructed from Early Holocene archaeological shells (14.13 °C) was 2.86 °C cooler than mean temperature recorded in modern shells (16.99 °C). Mean SST reconstructed from modern shells was ~1.04 °C warmer than the mean temperature of in situ thermometers (15.95 °C). Hence the paleo-SST data from archaeological sites 224A and Paposo Norte 9 enrich the Early Holocene nearshore paleoceanographic scenario of the Pacific coast of South America, with mean SST cooler than present-day SST. Our results validate the use of *F. maxima* shells as a SST proxy and contribute to a better understanding of the latitudinal distribution of the coastal upwelling regime during the Early Holocene, temporal changes in the structure of the Humboldt Current along the Holocene, and its influence on human adaptation through the prehistory of South America.

1. Introduction

Along the west coast of temperate South America, wind-driven upwelling of deep, cold and nutrient-rich water fuels high primary productivity, which maintains some of the largest pelagic fisheries in the planet (Chavez et al., 2008). This eastern boundary upwelling ecosystem, established ~4 million years ago with the closure of the Panamanian seaway (Ibaraki, 1997), also sustains large benthic fisheries that were key for the early human inhabitants of this coastline (Latorre et al., 2017; Olguín et al., 2015a, 2015b). The large-scale spatial configuration of the wind-driven coastal upwelling regime has changed over time. Indeed, the position of the regional maxima and the sources of upwelled water experienced pronounced latitudinal changes during the Holocene (Carré et al., 2016; Kim et al., 2002; Latorre et al., 2017; Mohtadi et al., 2004; Ortlieb et al., 2011). Evidence to date suggests that the transition from the humid environmental regime of the Early Holocene to the dominantly arid coast of western South America involved a reorganization of paleoceanographic circulation patterns from southern Peru to central-northern Chile (Carré et al.,

2016; Ortlieb et al., 2011). The large uncertainty around the spatial organization of these paleoceanographic changes limits proper interpretation of their effects on coastal environments and human societies in the past. Coupled studies on the isotope composition of modern and archaeological shellfish assemblages have proven to be a powerful tool for reconstructing oceanographic variability throughout the Holocene and prehistoric times (Carré et al., 2005b; Galimberti et al., 2017).

Our study aims to provide information on mean sea surface temperature (SST) during the Early Holocene using archaeological shells of *Fissurella maxima* as a paleoclimate proxy. In particular, we investigate past and present mean SST in the coastal Atacama desert (area of Taltal, 25°S) (Fig. 1), an area located halfway between southern Peru and central-northern Chile. We first calibrate the use of modern *F. maxima* (Fig. 2)—a ubiquitous mollusc in archaeological shell middens of the region—to generate a quantitative proxy for local mean SST. Subsequently, based on the relationship between SST and $\delta^{18}\text{O}$ composition in the calcium carbonate (CaCO_3) of *F. maxima*, we provide new information that contributes to understand better the latitudinal distribution of the coastal upwelling regime during the Early Holocene,

* Corresponding author.

E-mail addresses: carola.flores@ceaza.cl (C. Flores), emgayo@uc.cl (E.M. Gayo), dsalazar@uchile.cl (D. Salazar), bernardo.broitman@ceaza.cl (B.R. Broitman).

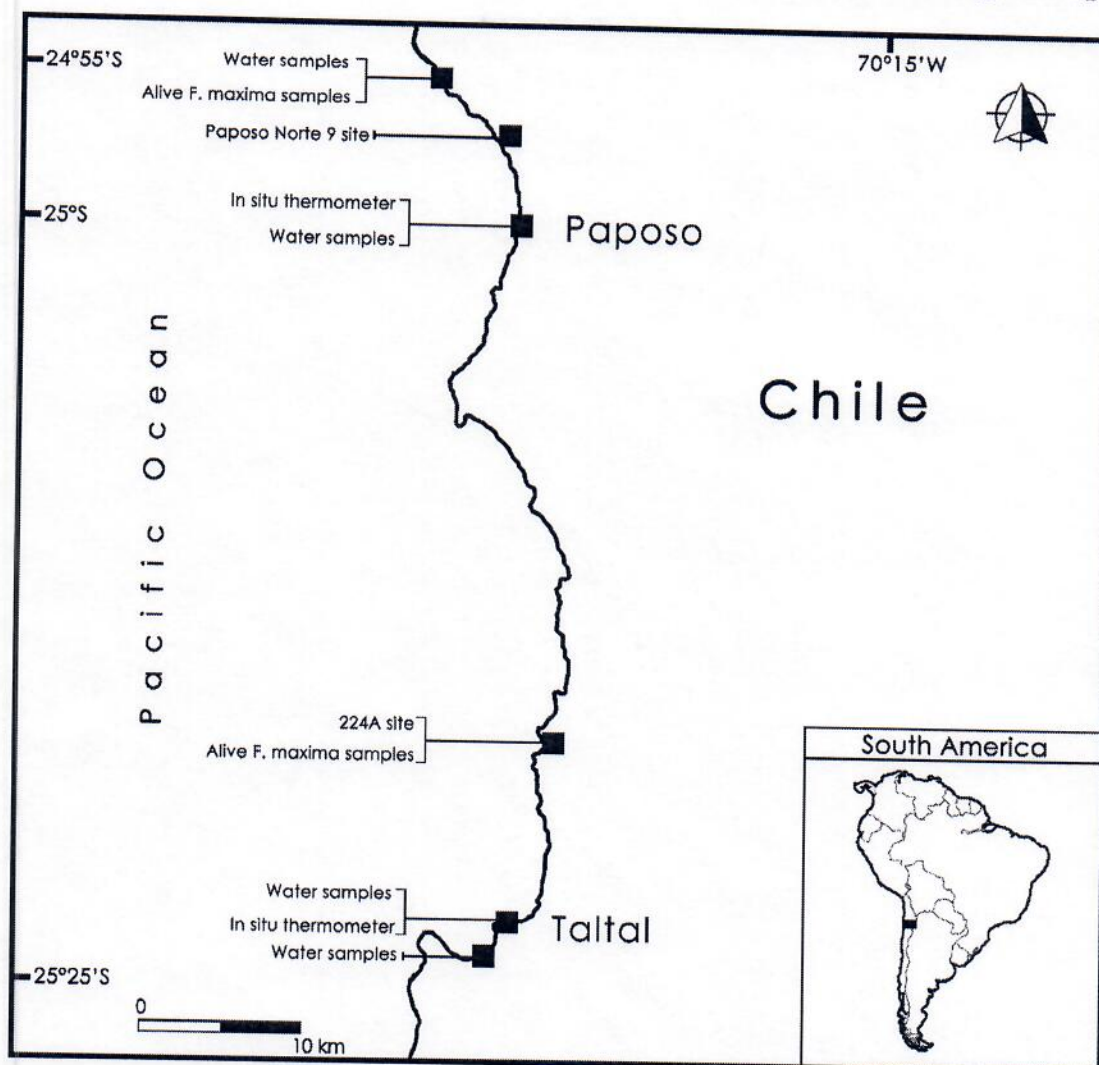


Fig. 1. Map of the study area showing places of collection of sea water samples and alive specimens of *F. maxima*, archaeological sites where shells of *F. maxima* were obtained, and location of in situ thermometers.

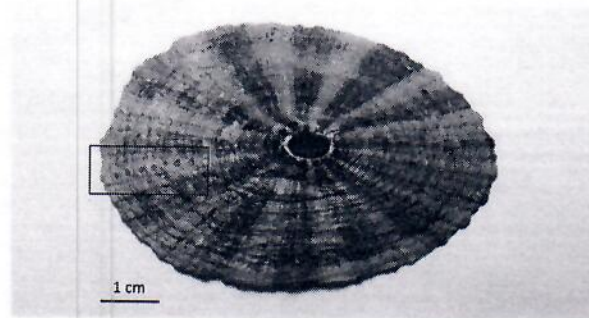


Fig. 2. *F. maxima* shell. The square marks carbonate microsamples.

temporal changes in the structure of the Humboldt Current along the Holocene, and its influence on human adaptation in the prehistory of South America.

2. Research background

Oxygen isotope ratios in mollusc CaCO_3 have been widely used to characterize past nearshore oceanographic conditions, particularly to

reconstruct SST patterns (e.g. Carré et al., 2012; Colonese et al., 2012; Glassow et al., 2012; Jew et al., 2016; Mannino et al., 2008; Prendergast and Schöne, 2017; Surge and Barrett, 2012). As molluscs grow, they deposit new shell layers by precipitating CaCO_3 from seawater (Wefer and Berger, 1991). However, only some species deposit biogenic CaCO_3 with $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ concentrations in equilibrium with water temperature. Biological factors (i.e. ontogeny or physiology) may disrupt the predictable linear relationship between SST, oxygen composition of seawater and biogenic carbonates (Bijma et al., 1999; Ford et al., 2010; McConnaughey, 1989). This implies that paleotemperature inferences from $\delta^{18}\text{O}_{\text{shells}}$ could be biased by kinetic and vital effects, leading to an offset between $\delta^{18}\text{O}_{\text{shell}}$ and $\delta^{18}\text{O}_{\text{water}}$.

Isotope studies of shells of coastal molluscs from archaeological sites along the south-eastern Pacific have been carried out in a limited number of sites. These studies have focused on the surf clam *Mesodesma donacium* from the southern coast of Peru (18°S) (Carré et al., 2014) and central Chile (31°S) (Carré et al., 2012), and on the whelk *Concholepas concholepas* from northern (23°S) (Vargas et al., 2006) and central Chile (33°S) (Falabella et al., 1991). Regarding nearshore SST reconstructions from the Early Holocene, cooler than present SST has been inferred for northern Chile (23°S) between 10,550 and 9120 cal yr BP (Vargas et al., 2006) and slightly cooler or similar than modern SST values have been obtained from central Chile (31°S), dated between 10,380 and

9460 cal yr BP (Carré et al., 2012). This paleoceanographic pattern, complemented with studies on ^{14}C reservoir ages, has been interpreted as the result of a latitudinal gradient in upwelling intensity along the Pacific coast of South America (Carré et al., 2014, 2016; Fontugne et al., 2004; Ortlieb et al., 2011).

Studies on modern marine ecosystems indicate that variations in coastal upwelling circulation lead to strong differences in productivity and abundance of marine resources over short spatial scales (i.e. tens of km, Broitman et al., 2001; Nielsen and Navarrete, 2004; Valdivia et al., 2013). Because pre-Hispanic populations that inhabited the Pacific coast of South America relied heavily on marine resources, marine productivity variation driven by oceanographic processes might have affected cultural trajectories, consumption and gathering patterns (e.g. Santoro et al., 2017). Archaeological evidence from the Peru–Chile region shows consistent changes in fishing–gathering strategies during the Holocene (Béarez et al., 2016; Olguín et al., 2014, 2015b; Rebolledo et al., 2016; Reitz et al., 2015, 2016; Salazar et al., 2015). For instance, Early Holocene archaeological sites (12000–10,000 cal yr BP) from southern Peru and the Taltal area show fish assemblages with low mean trophic level and composed mostly of cold-tolerant species. On the other hand, in sites dated later than 8500 cal yr BP the abundance of fish remains increases considerably, together with an increment of warm-tolerant species and a diversification in fish trophic levels, including pelagic predators (i.e. *Thyrites atum*) and open-sea taxa (i.e. *Xiphias gladius*, *Kajikia audax*) (Béarez et al., 2016; Olguín et al., 2014; Rebolledo et al., 2016; Reitz et al., 2015, 2016; Salazar et al., 2015).

3. Study area and environmental setting

The study area is located on the southern coast of the Atacama desert (Fig. 1), which encompasses vast areas with virtually no rain ($< 1 \text{ mm/yr}$) and lacking superficial hydrological resources (perennial rivers) (Houston, 2006). The core of this extreme landscape is currently located between 22 and 25°S, where vegetation is almost absent except for isolated fog-driven coastal vegetation formations on the western slopes of the Coast Range (Arroyo et al., 1988; Marquet et al., 1998; Rundel et al., 1991) and around scattered brackish springs along the coastal platform (Herrera and Custodio, 2014; Herrera et al., 2018). Moisture sources include the coastal fog locally known as “*camanchaca*” (Cereceda et al., 2008; Garreaud et al., 2008; Rundel et al., 1991) and summer coastal rains during strong El Niño years (Garreaud et al., 2003). These occasional but intense rainfall events are usually short-lived (~1–2 days) (Wilcox et al., 2016), so it is unlikely that they affect the isotopic composition of nearshore sea waters. The topography of the coastal Atacama desert is characterized by narrow coastal terraces (~500 m wide) with steep slopes from the coast to 2000 m above sea level. Extreme marine and littoral productivity along this coast (Montecino et al., 2005; Thiel et al., 2007), is modulated by oceanographic factors such as ENSO (El Niño Southern Oscillation, cycle of warming and cooling events over the equatorial Pacific Ocean) variability and local upwelling intensity around headlands (Barber and Chavez, 1983; Chavez et al., 2008).

4. Biology and ecology of *F. maxima*

F. maxima (Sowerby 1833–1835) (Fig. 2) is an eastern south Pacific keyhole limpet, common on rocky shores between southern Peru (10°S) and central Chile (36°S) (Bretos, 1982; Bretos et al., 1983). This species inhabits the low intertidal and upper subtidal zones down to 5 m depth, below stands of kelp of the genus *Lessonia*, which is a common part of the diet of *F. maxima* (McLean, 1984; Osorio et al., 1988). They can live between 7 and 10 years, reaching 50 mm in ca. 2 years (Bretos, 1982). Mature (reproductive) specimens are 48–65 mm long, with maximum adult size ranging from 80 to 135 mm long (McLean, 1984). Metabolic activity is strongly influenced by seasonal conditions, especially ocean water temperature. Reproductive periods (spawning) are in late

November–December (end of spring) and July–August (winter) (Bretos et al., 1983; McLean, 1984). Most molluscs respond to seasonal processes by slowing down or arresting growth during periods of increased metabolic demand (Schöne, 2008; Wilbur and Owen, 1964). Therefore, despite the lack of studies on the effect of changes in water temperature on the performance of *F. maxima*, it is likely that this keyhole limpet slows growth during spawning periods at the end of spring and during winter (Bretos et al., 1983; McLean, 1984).

5. Material and methods

5.1. Shell sampling and processing

Eight modern specimens of *F. maxima* were collected alive during spring 2015 (November), summer 2016 (February) and spring 2016 (November) from the surf area of rocky shores at two locations. Shell sizes ranged from 62 to 101 mm total length (measured between anterior and posterior shell edge (Jerardino and Navarro, 2008)). Four shells were collected near Taltal and four shells near Paposo, at the southern and northern limits of our study area, respectively (Fig. 1).

Archaeological shells of *F. maxima* were collected from rockshelter site 224A and Paposo Norte 9 (Fig. 1), with four shells collected at each archaeological site from stratigraphic layers associated with their earliest occupations. These sites show Early Holocene deposits from 20 to 40 cm thick with evidence of residential refuse located both inside and outside the rockshelter's drip line. Hearths are intersected with middens or ash layers containing mollusc shells, fish, bird and mammal bones, as well as lithic debris and tools, attesting to the cultural origins of the deposits (Salazar et al., 2013, 2015, 2017). Shellfish remains from these two archaeological sites contained high abundance of limpet shells throughout their occupation (Olguín et al., 2015a).

Early Holocene deposits from archaeological rockshelter site 224A have been dated between 12,426 and 10,263 cal yr BP based on three radiocarbon determinations of charcoal and shell samples. This site is located in the western foothills of the Coast Range near the current mouth of the Cascabeles Ravine, 12 km north of the city of Taltal and $< 300 \text{ m}$ from today's coastline (Salazar et al., 2015, 2017). The archaeological rockshelter site of Paposo Norte 9, with dates ranging between 11,250 and 10,566 cal yr BP (on charcoal samples), is located nearly 60 km north of Taltal and around of 200 m from the current coastline (Salazar et al., 2015, 2017).

The chronological constraint of *F. maxima* shells sampled from each archaeological site was assigned by considering the stratigraphic association between these shells and the age of the nearest dated material. Sampled shells of the three radiocarbon dates from site 224A have an associated date of 11,010 cal yr BP ($10,530 \pm 30^{14}\text{Cyr BP}$, Salazar et al., 2017). The associated date of shell samples retrieved from the rockshelter site Paposo Norte 9 is 11,206 cal yr BP ($9813 \pm 37^{14}\text{Cyr BP}$, Salazar et al., 2017).

Prior to sample extraction for isotope analysis, modern and archaeological shells were scraped to remove any organic material from the outer shell layer, then individually rinsed in deionized water and subsequently etched with muriatic acid (HCL 0.2 N) to remove diagenetically altered carbonate (Bailey et al., 1983). Finally, modern and archaeological shells were dried at 85 °C, and microsamples were collected every two millimeters (including sampling holes) along their growth axis, with eight samples taken along a ~20 mm transect from the edge of each shell towards the apical aperture. This procedure was chosen following previous studies done in California and the Caribbean (Flores, 2017; Glassow et al., 2012; Jew et al., 2016; Thakar, 2016) (Fig. 2). A total of 128 shell carbonate samples were obtained from archaeological and modern shells. Samples were drilled manually with a Foredom flexible shaft motor drill linked to a Dremel micro motor, using a 0.5 mm carbide bit. Each drill hole was about 0.5 mm in diameter and yielded 20–90 µg of powdered shell carbonate. The drill bit was cleaned in an ethanol bath and the shell was cleaned with

compressed air between samplings in order to avoid cross-contamination. Samples of powdered carbonate were analysed in the Stable Isotope Facility at the University of California, Davis. Instrument precision (1σ) is estimated as $\pm 0.03\text{‰}$ for $\delta^{13}\text{C}$ and $\pm 0.05\text{‰}$ for $\delta^{18}\text{O}$ and their values are expressed in relation to the international Vienna Pee Dee Belemnite (VPDB) scale.

Kinetic isotope fractionation can influence carbonate deposition in shells by inducing depleted values of both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ in comparison to seawater (Fenger et al., 2007; McConnaughey, 1989). The simultaneous depletion of ^{13}C and ^{18}O isotopes leads to a quasi-linear relationship between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in shells during the calcification processes (McConnaughey, 1989). Therefore if no correlation is found between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values in a shell, kinetic isotope effects were minimum during shell formation. Hence in order to evaluate the kinetic effect on the formation of modern and archaeological *F. maxima* shells from the study area, a Pearson correlation analysis was performed for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of each carbonate microsample.

The vital effect can influence paleotemperature inferences from $\delta^{18}\text{O}_{\text{shells}}$, leading to an offset between $\delta^{18}\text{O}_{\text{shell}}$ and $\delta^{18}\text{O}_{\text{water}}$ (Bijma et al., 1999; Ford et al., 2010; McConnaughey, 1989). Because inter or intraspecific biological factors (e.g. ontogeny, calcification rates) that might disrupt the predictable linear relationship between SST, oxygen composition of seawater and biogenic carbonate are species-specific (Fenger et al., 2007; Ferguson et al., 2011; Ford et al., 2010; Gutiérrez-Zugasti et al., 2017; Owen et al., 2002; Prendergast et al., 2013; Prendergast and Schöne, 2017; Schifano and Censi, 1983), it is necessary to evaluate the presence of a vital effect in the deposition of *F. maxima* shells.

We tackled this issue by computing the offset from isotopic equilibrium following the procedure presented in Gutiérrez-Zugasti et al. (2017). A comparison was made between $\delta^{18}\text{O}_{\text{shell}}$ values from the edge of each modern *F. maxima* shell and the predicted $\delta^{18}\text{O}_{\text{shell}}$ calculated from seawater temperatures and $\delta^{18}\text{O}_{\text{seawater}}$. Predicted values were calculated considering averaged SST recorded at the Taltal and Paposo areas for the 4 months previous to shell collection (November 2015, February 2016 and November 2016, Table 2), and $\delta^{18}\text{O}_{\text{seawater}}$ resulting from the mean of measurements available per area in November 2015 and February 2016 (Table 1). Since information on local seawater isotope-oxygen composition was not available for November 2016, we used $\delta^{18}\text{O}_{\text{seawater}}$ for the preceding 2015 spring season. The equation of Friedman and O'Neil (1997) for calcite (Eq. (1)) was applied to interconvert $\delta^{18}\text{O}_{\text{shell}}$ values between PDB and SMOW.

$$\delta^{18}\text{O}_{\text{SMOW}} = 1.03086(\delta^{18}\text{O}_{\text{PDB}}) + 30.86 \quad (1)$$

Subsequently, the Friedman and O'Neil (1977) equations for calcite

(Eq. (2)) and water (Eq. (2)) were used to calculate predicted $\delta^{18}\text{O}_{\text{shell}}$ values.

$$1000 \ln \alpha = 2.78 \times 10^6 = T^2 - 2.89 \quad (2)$$

where T is the temperature measured in degrees Kelvin and α is the fractionation between water and calcite described by the equation:

$$\alpha = (1000 + \delta^{18}\text{O}_{\text{shell}} (\text{SMOW})) / (1000 + \delta^{18}\text{O}_{\text{water}} (\text{SMOW})) \quad [3]$$

5.2. Environmental parameters

Monthly mean SST records obtained from self-contained submersible temperature dataloggers (HOBO U22, Onet Corp., Ma USA) attached to local pier pilings in Taltal and Paposo (Fig. 1) were used to characterize the seasonal SST cycle in the study area. The accuracy of HOBO U22 water temperature loggers is $\pm 0.20^\circ\text{C}$. These in situ thermometers were located approximately 1 m below mean lower low water (MLLW) and recorded water temperature every 10 min during three years from January 2013 to December 2016.

To provide a broader overview of ocean temperature conditions across the study area we used night time level-3, 8-day, 16 km² satellite SST from the Moderate Resolution Imaging Spectroradiometer (MODIS) imagery downloaded from the NASA website (<http://oceancolor.gsfc.nasa.gov/>). Over a period overlapping the in situ thermometer SST records described above, we calculated the monthly mean satellite SST of the coastal zone between Paposo and Taltal by averaging between images with > 80% valid pixels over an area extending 24 km offshore and 48 km alongshore (e.g. 288 km², white square in Fig. 4).

To characterize the isotope composition of local sea water ($\delta^{18}\text{O}_{\text{water}}$ and $\delta^2\text{H}_{\text{water}}$) we collected eight 5 ml samples from the shore in November 2015 and eight in February 2016 from Taltal and Paposo (Fig. 1). At each location, sea water samples were obtained from the surf zone and from fishing wharves. The oxygen and hydrogen isotope composition of these samples was analysed at the Isotope Biogeochemistry Laboratory, Department of Oceanography, University of Concepcion, using a Picarro L2130-i Analyser. The results obtained were normalized to the Vienna Standard Mean Ocean Water (VSMOW) scale through repeated analysis of 4 laboratory working standards calibrated relative to VSMOW: distilled water ($\delta^{18}\text{O} = -13.32\text{‰} \pm 0.02\text{‰}$, $\delta^2\text{H} = -84.41\text{‰} \pm 0.10\text{‰}$), snow ($\delta^{18}\text{O} = -12.61\text{‰} \pm 0.02\text{‰}$, $\delta^2\text{H} = -102.17\text{‰} \pm 0.09\text{‰}$), sea water ($\delta^{18}\text{O} = -0.34\text{‰} \pm 0.05\text{‰}$, $\delta^2\text{H} = +0.88\text{‰} \pm 0.17\text{‰}$) and mineral water ($\delta^{18}\text{O} = -13.17\text{‰} \pm 0.03\text{‰}$, $\delta^2\text{H} = -96.66\text{‰} \pm 0.08\text{‰}$).

Table 1
Seawater $\delta^{18}\text{O}$ values obtained from samples collected at Taltal and Paposo.^a

Code	Area of collection	UTM North	UTM East	Season of collection	Month of collection	Year	$\delta^{18}\text{O}_{\text{VSMOW}}/\text{‰}$	S.D.	$\delta^2\text{H}_{\text{VSMOW}}/\text{‰}$	S.D.
P1	Taltal	7,189,875	351,172	Spring	November	2015	-0.50	0.03	+0.3	0.11
P2	Taltal	7,189,875	351,172	Spring	November	2015	-0.31	0.03	+0.8	0.08
P3	Paposo	7,233,255	351,793	Spring	November	2015	+0.28	0.06	+2.9	0.18
P4	Paposo	7,233,255	351,793	Spring	November	2015	+0.48	0.02	+3.6	0.11
P15	Paposo	7,242,020	346,816	Spring	November	2015	+0.74	0.03	+4.3	0.06
P16	Paposo	7,242,020	346,816	Spring	November	2015	-0.35	0.03	+1.3	0.07
P8	Taltal	7,190,974	351,839	Spring	November	2015	-0.37	0.06	+0.8	0.10
P9	Taltal	7,190,974	351,839	Spring	November	2015	+0.13	0.20	+2.7	0.36
P5	Paposo	7,242,020	346,816	Summer	February	2016	-0.35	0.04	+1.3	0.17
P6	Paposo	7,242,020	346,816	Summer	February	2016	-0.21	0.13	+1.4	0.18
P12	Paposo	7,233,255	351,793	Summer	February	2016	+0.57	0.03	+4.1	0.18
P14	Paposo	7,233,255	351,793	Summer	February	2016	-0.20	0.02	+1.9	0.11
P7	Taltal	7,189,135	350,154	Summer	February	2016	+0.07	0.05	+1.9	0.32
P10	Taltal	7,189,135	350,154	Summer	February	2016	-0.21	0.02	+1.5	0.14
P11	Taltal	7,191,004	351,776	Summer	February	2016	+0.02	0.05	+2.3	0.12
P13	Taltal	7,191,004	351,776	Summer	February	2016	+0.00	0.02	+2.4	0.05
MEAN							-0.01	0.05		

^a Sampling places geo—referenced in Universal Transverse Mercator (UTM) (WSG 84).

5.3. $\delta^{18}\text{O}_{\text{shell}}$ and reconstructed temperatures

In order to use the correct carbonate temperature equation to reconstruct water temperature we assessed the carbonate composition (calcite vs. aragonite) of *F. maxima* shells. Results of X-Ray diffractometry (XRD) analyses on one modern *F. maxima* shell showed that calcium carbonate of its inner and outer shell layers were composed of aragonite and calcite, respectively, which matches with a previous study on *Fissurella crassa* (Boogild, 1930 in McLean, 1984). Hence, while collecting carbonate samples from modern and archaeological shells, care was taken to ensure that drilled holes did not penetrate into the inner layer of the shell (Keith et al., 1964). XRD analyses were done at the Institute of Applied Economic Geology, University of Concepción, Chile using a BRUKER D4 equipped with a Lynxeye detector and operated with Cu radiation with a filter of Ni K beta radiation.

Previous SST reconstructions for southern Peru and north-central Chile have used different equations to translate $\delta^{18}\text{O}_{\text{shell}}$ into SST (Carré et al., 2005a, 2005b, 2012). The equations employed by Carré et al. (2005b) and Grossman and Ku (1986) are appropriate for shells with calcium carbonate composed of aragonite (e.g. *M. donacium*). Equations for calcite have not been used along the coast of South America except for a study in the Beagle Channel, southern Patagonia, based on limpet shells (*Nacella deaurata* and *N. maguellanica*) (Colonese et al., 2012), which used the calcite equation originally proposed by Wanamaker Jr. et al. (2007) for a north Atlantic (Greenland) mussel species (*Mytilus edulis*).

We chose for our study the carbonate temperature equation (Eq. (4)) developed by Ford et al., (2010) for *Mytilus californianus* from the north-eastern Pacific (California). This mussel species has a shell composed of calcite, like *F. maxima*. The conversion of $\delta^{18}\text{O}_{\text{shell}}$ signature into paleoSST was calculated as follows:

$$1000 \ln \left(\frac{(1000 + \delta^{18}\text{O}_{\text{equilibrium calcite}})}{(1000 + \delta^{18}\text{O}_{\text{seawater}})} \right) = 18.734 (10^3 \text{ T}^{-1}) - 33.776 \quad (4)$$

where T is temperature in degrees Kelvin, isotope values of sea water are reported relative to Standard Mean Ocean Water (SMOW) and isotope values of calcite are reported relative to Vienna Pee Dee Belemnite (VPDB). To convert Kelvin to Celsius we subtracted 273.15 from SST values. The $\delta^{18}\text{O}_{\text{seawater}}$ value used in the equation corresponds to the mean value of local measurements of sea water obtained from the Taltal and Paposo areas (Fig. 1, Table 1). Given that our shell sampling strategy does not control for shell growth rates or chronology of shell microsamples, it was not possible to calculate the slope of the regression line between instrumental SST and $\delta^{18}\text{O}_{\text{shell}} - \delta^{18}\text{O}_{\text{seawater}}$ of each shell microsample. Also, as variation in growth rate of sampled *F. maxima* may over or underestimate the slope, it is not possible to test the slope of the Ford et al. (2010) equation. Consequently, sea surface temperature calculation of modern and archaeological $\delta^{18}\text{O}_{\text{shell}}$ values was carried out using the slope provided by Eq. (4) (Ford et al., 2010).

Temporal fluctuations in the extension of global ice sheets influence $^{18}\text{O}/^{16}\text{O}$ ratios of seawater and thus $^{18}\text{O}/^{16}\text{O}$ ratios in carbonate micro and macrofossils like marine mollusc shells (Aharon and Chappell, 1986; Duplessy et al., 2002). Archaeological shells used for this study come from two Early Holocene rockshelter sites dated between 12,426 and 10,566 cal yr BP. During this time there were still some remains of glacial ice sheets, so higher than present $\delta^{18}\text{O}_{\text{seawater}}$ values are expected. To account for the ice volume effect on sea water $\delta^{18}\text{O}$, an ice volume correction of -0.463‰ was applied to $\delta^{18}\text{O}$ values of shells from site 224A based on their associated date of 11,010 cal yr BP. The correction for $\delta^{18}\text{O}$ values of shells from Paposo Norte 9 site was -0.445‰ based on the associated date of 11,206 cal yr BP. Correction values were calculated using the sea level reconstruction from Lambeck and Chappell (2001) and a maximum ice volume effect of 1.05‰ for the last glacial maximum (LGM) (Duplessy et al., 2002).

$$\text{Ice volume correction} = (\text{sl}/145) \times 1.05 \quad (5)$$

where sl is the global sea level for the time period under study (Lambeck and Chappell, 2001) divided by the lowest sea level recorded from the period between last glacial maximum to the end of major ice sheet decay (preset time) (Lambeck and Chappell, 2001), and then multiplied by the difference of seawater $\delta^{18}\text{O}$ values between LGM and today (Duplessy et al., 2002).

6. Results

6.1. Environmental parameters

Continuous thermometer SST records at Taltal and Paposo indicated a long-term mean of 15.95°C with a range of 3.75°C between the warmest (mean of 18°C , summer, February 2016) and coolest month (mean of 14.25°C , spring, September 2014) (Fig. 3, Table 2). Satellite SST for the coastal zone of the study area indicates a long-term mean SST of 16.88°C , with a range of 6.51°C between the warmest (mean of 20.76°C , summer, February 2016) and coolest month (mean of 14.25°C , winter, August 2013) (Fig. 4, Table 3). The Pearson correlation between monthly SST values from thermometers and satellite measurements for the coastal area between Paposo and Taltal (Fig. 4) was strong and highly significant ($r = 0.778$, $p = 0.000$), with satellite SST values consistently $\sim 1\text{--}2^\circ\text{C}$ warmer than in situ records (Fig. 5, Fig. 6).

A mean $\delta^{18}\text{O}_{\text{seawater}}$ value of $-0.01 \pm 0.05\text{‰}$ was obtained from 16 water samples collected at Taltal and Paposo during November 2015 and February 2016 (Table 1). Seasonal mean values did not differ significantly between spring ($+0.01 \pm 0.46\text{‰}$) and summer ($-0.04 \pm 0.29\text{‰}$) (Mann-Whitney U = 30.50, $p = 0.91$) (Table 1). Mean $\delta^{18}\text{O}_{\text{seawater}}$ values for both seasons closely followed the average value for the surface ocean, but were slightly lower than the southern Peruvian coast ($0.13\text{--}0.16\text{‰}$, Carré et al., 2005b, 2012).

6.2. Shell oxygen isotopes ($\delta^{18}\text{O}_{\text{shell}}$)

To evaluate the kinetic effect on the formation of modern and archaeological *F. maxima* shells, a Pearson correlation analysis was performed for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values of modern and archaeological carbonate microsamples. For the 64 microsamples of modern *F. maxima* shells, a non-significant relationship ($r = 0.273$, $p = 0.029$) was found between their $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values (raw values in Supplementary Data

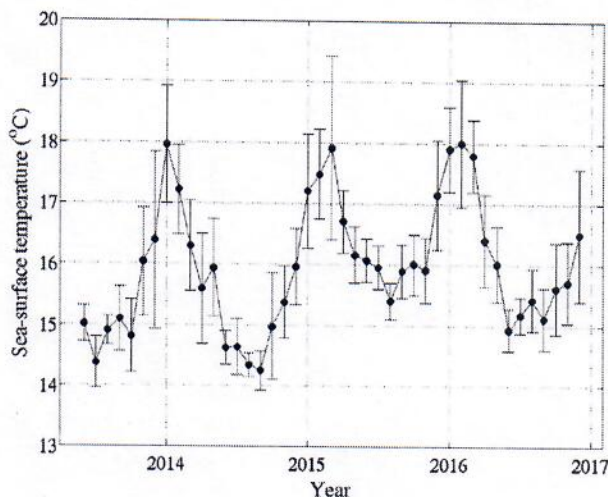


Fig. 3. Monthly mean sea surface temperature record for the study area from in situ thermometers at Paposo and Taltal from 2013 to 2016. Error bars represent one standard deviation.

Table 2
Monthly mean SST (°C) from in situ thermometers at Taltal and Paposo.

Year	Month	SST (°C)					
		Mean	Median	Max	Min	S.D.	Var
2013	June	15.02	15.08	15.56	14.15	0.29	0.09
2013	July	14.38	14.47	15.01	13.23	0.42	0.18
2013	August	14.92	14.92	15.32	14.29	0.24	0.06
2013	September	15.10	15.13	16.01	13.86	0.53	0.28
2013	October	14.82	14.94	15.75	13.35	0.60	0.36
2013	November	16.04	15.82	17.53	14.72	0.88	0.78
2013	December	16.40	16.65	19.21	14.02	1.45	2.10
2014	January	17.96	18.10	19.70	16.27	0.96	0.92
2014	February	17.22	17.33	18.54	15.34	0.73	0.53
2014	March	16.30	16.41	17.74	15.05	0.74	0.55
2014	April	15.60	15.58	17.12	14.09	0.90	0.81
2014	May	15.94	15.91	17.47	14.63	0.80	0.64
2014	June	14.63	14.64	15.00	14.18	0.28	0.08
2014	July	14.64	14.84	15.15	13.57	0.46	0.21
2014	August	14.35	14.34	14.73	13.87	0.20	0.04
2014	September	14.25	14.33	14.98	13.67	0.33	0.11
2014	October	14.98	15.11	16.36	13.46	0.88	0.77
2014	November	15.39	15.51	16.18	14.27	0.59	0.34
2014	December	15.97	15.98	17.24	14.88	0.62	0.39
2015	January	17.20	17.12	19.27	15.35	0.94	0.88
2015	February	17.48	17.50	19.12	16.37	0.74	0.54
2015	March	17.91	17.30	20.51	15.91	1.51	2.28
2015	April	16.71	16.74	17.87	15.63	0.51	0.26
2015	May	16.16	16.22	16.99	15.31	0.45	0.21
2015	June	16.07	15.96	16.75	15.52	0.35	0.13
2015	July	15.96	15.91	16.86	15.35	0.36	0.13
2015	August	15.41	15.43	15.94	14.74	0.30	0.09
2015	September	15.90	15.90	16.99	15.02	0.44	0.19
2015	October	16.01	16.06	17.00	14.84	0.49	0.24
2015	November	15.91	15.92	17.03	15.09	0.53	0.28
2015	December	17.15	17.47	18.56	15.46	0.90	0.81
2016	January	17.90	17.87	19.45	16.75	0.70	0.48
2016	February	18.00	18.10	19.52	16.07	1.05	1.10
2016	March	17.79	17.81	19.18	16.70	0.60	0.35
2016	April	16.40	16.14	18.50	15.49	0.76	0.57
2016	May	16.02	15.95	17.26	15.08	0.62	0.38
2016	June	14.95	14.97	15.51	13.88	0.35	0.12
2016	July	15.18	15.17	15.75	14.45	0.30	0.09
2016	August	15.43	15.37	16.32	14.60	0.51	0.26
2016	September	15.12	15.07	15.97	14.06	0.51	0.26
2016	October	15.62	15.57	16.92	14.59	0.75	0.56
2016	November	15.72	15.82	16.89	13.88	0.67	0.44
2016	December	16.50	16.40	18.46	14.82	1.09	1.18
TOTAL		15.95	15.77	20.51	13.23	1.26	1.58

1), which discounts kinetic effects on the formation of modern shells. A non-significant relationship ($r = -0.170$, $p = 0.179$) was also found in carbonate microsamples of archaeological shells (raw values in Supplementary Data 1), excluding kinetic effects on the formation of these specimens.

To evaluate whether *F. maxima* precipitates its shell in isotopic equilibrium with surrounding water (vital effect), predicted and measured $\delta^{18}\text{O}_{\text{shell}}$ values from the edge of modern *F. maxima* shells were compared, obtaining a moderate inverse but non-significant correlation ($r = -0.561$, $p = 0.148$). SST and $\delta^{18}\text{O}_{\text{water}}$ data from the Paposo and Taltal areas predict $\delta^{18}\text{O}_{\text{shell}}$ values ranging from -0.51 to $+0.34\text{‰}$ with an average of -0.20‰ (Table 4). Measured $\delta^{18}\text{O}_{\text{shell}}$ values at the edge of modern *F. maxima* were consistently enriched, ranging from $+0.44\text{‰}$ to $+1.06\text{‰}$, mean = $+0.80\text{‰}$ (Table 4). This positive deviation of measured $\delta^{18}\text{O}_{\text{shell}}$ values showed high variability among modern *F. maxima* shell samples (Fig. 7), with an average offset of $1 \pm 0.5\text{‰}$. Despite this variability, the relationship between predicted and measured $\delta^{18}\text{O}_{\text{shell}}$ was similar in the two localities (Paposo and Taltal) and seasons (austral spring versus summer), which suggests that environmental factors are not driving the observed deviations from the isotopic equilibrium.

The average offset of 1‰ was subtracted from measured $\delta^{18}\text{O}_{\text{shell}}$

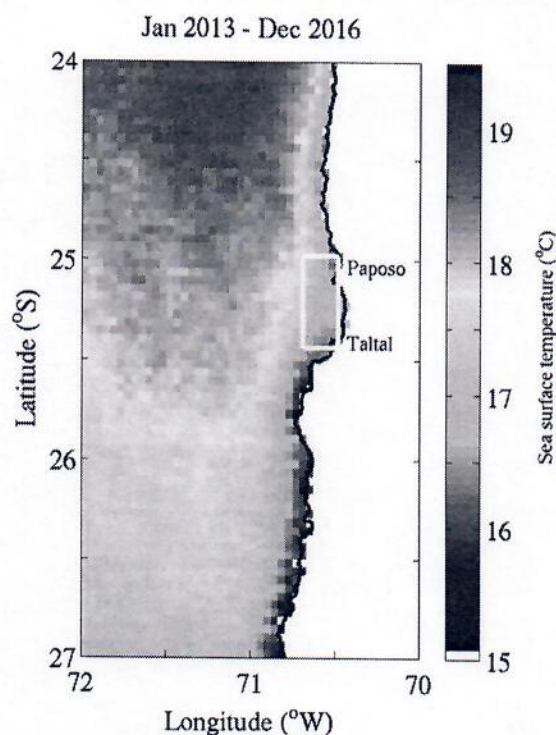


Fig. 4. Mean sea surface temperature between Paposo and Taltal recorded in satellites from 2013 to 2016. The white square indicates the area considered for satellite SST analyses.

values of modern *F. maxima* shells. Mean $\delta^{18}\text{O}_{\text{shell}}$ values obtained after correction are summarized in Table 5 (raw values in Supplementary Data 1) and range between -1.20‰ and $+0.06\text{‰}$ (mean = $+0.61\text{‰}$, SD = $+0.35\text{‰}$). Mean $\delta^{18}\text{O}_{\text{shell}}$ values obtained from modern *F. maxima* shells without the offset correction are summarized in Table 6 (raw values in Supplementary Data 1) and range between -0.20‰ and $+1.06\text{‰}$ (mean = $+0.39\text{‰}$, SD = $+0.35\text{‰}$). Mean $\delta^{18}\text{O}_{\text{shell}}$ values from archaeological shells without the offset correction are slightly enriched in ^{18}O compared to modern counterparts, ranging from $+0.00\text{‰}$ to $+1.72\text{‰}$ (mean = $+1.03\text{‰}$, SD = $+0.35\text{‰}$) (Table 6). Microsample A.C.4.G from archaeological shell ID A.C.4. was excluded from analyses performed in this study as it yielded an outlying $\delta^{18}\text{O}$ value of $+3.31\text{‰}$ (raw values in Supplementary Data 1). Consequently, for the purpose of the study only seven microsamples were considered from shell ID A.C.4 and this outlier value is not included in Table 6.

6.3. Reconstructed temperatures

To evaluate a vital effect correction on SST reconstruction, the $+1\text{‰}$ offset was subtracted from modern *F. maxima* $\delta^{18}\text{O}_{\text{shell}}$ values. Corrected *F. maxima* $\delta^{18}\text{O}_{\text{shell}}$ values were then converted to SST using Eq. (4) (Ford et al., 2010); the mean SST obtained was 21.56°C with a lower and upper mean SST value of 20.35°C (Shell ID B.C.2) and 22.53°C (Shell ID L.F.P.2) (Table 7). Applying the same SST Equation (Ford et al., 2010) to modern *F. maxima* $\delta^{18}\text{O}_{\text{shell}}$ values but without the offset correction, the mean SST obtained was 16.99°C with lower and upper mean SST values of 15.82°C (Shell ID B.C.2) and 17.93°C (Shell ID L.F.P.2) (Table 8). Finally, using Eq. (4) and considering the ice-volume effect, mean SST from archaeological *F. maxima* $\delta^{18}\text{O}_{\text{shell}}$ values (without the offset correction) was 14.13°C with minimum and maximum mean SST values of 13.36°C (Shell ID A.C.2) and 15.52°C (Shell ID P.F.4), respectively (Table 8).

Table 3

Monthly mean SST (°C) from satellite information of the area between Tal-tal and Paposo.

Year	Month	Mean (°C)
2013	June	16.06
2013	July	15.42
2013	August	14.25
2013	September	14.64
2013	October	14.49
2013	November	15.30
2013	December	15.98
2014	January	17.60
2014	February	19.18
2014	March	18.80
2014	April	18.62
2014	May	17.32
2014	June	17.08
2014	July	15.64
2014	August	15.16
2014	September	14.86
2014	October	14.72
2014	November	15.97
2014	December	15.97
2015	January	No info
2015	February	18.66
2015	March	19.35
2015	April	18.72
2015	May	18.25
2015	June	17.44
2015	July	15.73
2015	August	15.56
2015	September	15.70
2015	October	15.72
2015	November	15.86
2015	December	16.89
2016	January	19.33
2016	February	20.76
2016	March	19.76
2016	April	18.94
2016	May	18.19
2016	June	17.74
2016	July	15.43
2016	August	15.06
2016	September	14.72
2016	October	15.08
2016	November	15.78
2016	December	17.61
Mean		16.88

7. Discussion

To provide a correction value for SST records obtained from satellite data, we compared mean SST of the study area recorded by thermometers and satellites between January 2013 and December 2016 (Fig. 1). The correction value obtained from this comparison is relevant for cases when only satellite SST data is available for comparison with reconstructed shell SST (i.e. Ferguson et al., 2011; Flores, 2017; Glassow et al., 2012; Jew et al., 2016; Prendergast and Schöne, 2017). Mean SST recorded by satellite was 0.93 °C higher than mean SST recorded by thermometers during the three year period (Table 9). The maximum monthly mean SST recorded by satellite was 2.76 °C higher than maximum mean SST from thermometers. In contrast, the minimum monthly mean SST was 14.25 °C from both satellites and thermometers (Table 7). The 0.93 °C difference between monthly thermometer and satellite SST records was expected from the radiative effect of the adjacent landmass and is in line with reports from south-central Chile and other coastal locations worldwide (Aravena et al., 2014). The strong linear relationship between satellite and thermometer SST indicates that both sources of information provide a reliable view of SST variability over the study area (Fig. 5). Nevertheless, as mean SST recorded by satellite was 0.96 °C higher than thermometers, this difference has to be considered when using satellite estimates for mean SST.

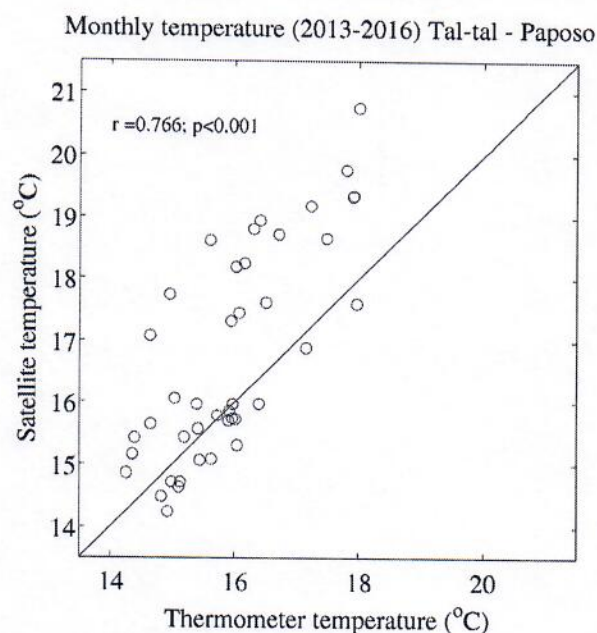


Fig. 5. Linear correlation between monthly sea surface temperature values for in situ thermometers and satellite.

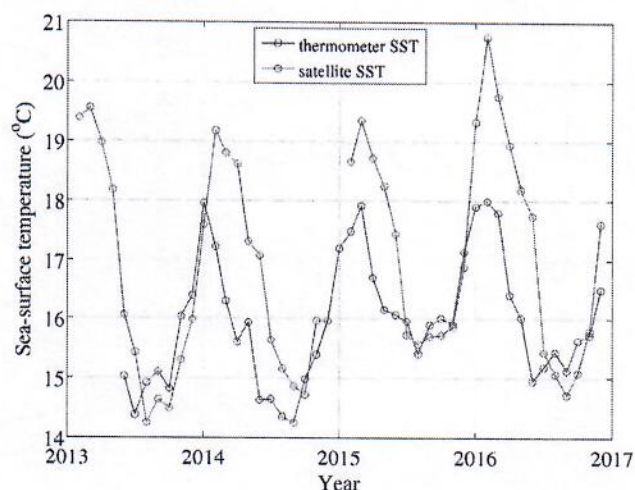


Fig. 6. Monthly mean SST records from in situ thermometers and satellite for the study area from January 2013 to December 2016.

As mentioned previously, vital effect can cause isotope disequilibrium in carbonate skeletons, which is reflected by $\delta^{18}\text{O}_{\text{shell}}$ values more positive than expected equilibrium values. The average offset estimated for modern *F. maxima* shell edges is $+1 \pm 0.5\text{‰}$ and therefore is coherent with a positive deviation of measured $\delta^{18}\text{O}_{\text{shell}}$ values (Fig. 7). Studies on *Patella* species from different locations have shown a consistent positive offset, ranging between 0.2‰ and 1.3‰ (Cohen and Tyson, 1995; Colonese et al., 2012; Fenger et al., 2007; Ferguson et al., 2011; Gutiérrez-Zugasti et al., 2017; Parker et al., 2017; Prendergast and Schöne, 2017). The calculated offset for *F. maxima* is close to the upper limit identified in isotope studies on the limpet *Patella vulgata* (1.01‰) from the eastern coast of England (Fenger et al., 2007) and *Patella candei crenata* (1.3‰) from the Canary Islands (Parker et al., 2017).

When the offset value of $1 \pm 0.5\text{‰}$ is subtracted from modern *F. maxima* $\delta^{18}\text{O}_{\text{shell}}$, the reconstructed mean SST ($21.56 \text{ °C} \pm 2.58$, Table 7) is $\sim 5.61 \text{ °C}$ warmer than mean temperatures recorded by in

Table 4

Parameters employed to estimate isotope fractionation offset of measured $\delta^{18}\text{O}_{\text{calcite}}$ at the edge of modern *F. maxima* shells.^a

Shell sample	Area of collection	Season of collection	Measured calcite $\delta^{18}\text{O}$ (‰, PDB)	Measured calcite $\delta^{18}\text{O}$ (‰, SMOW)	Seawater $\delta^{18}\text{O}$ (‰, SMOW)	Thermometer mean SST (°C)	Predicted calcite $\delta^{18}\text{O}$ (‰, SMOW)	Predicted calcite $\delta^{18}\text{O}$ (‰, PDB)	Offset ‰
B.C.2.A.	Taltal	November 2015	+1.02	+31.91	+0.26	16.14	+30.44	−0.41	−1.43
B.P6.2.A	Taltal	February 2016	+1.06	+31.95	−0.03	17.65	+30.33	−0.51	−1.57
Z.P6.1.A	Paposo	February 2016	+0.65	+31.53	−0.05	16.82	+30.5	−0.35	−1.00
Z.P6.2.A	Paposo	February 2016	+0.53	+31.41	−0.05	16.82	+30.5	−0.35	−0.88
B.C.P.1.A	Taltal	November 2016	+0.93	+31.82	−0.26	15.72	+30.54	−0.31	−1.24
B.C.P.2.A	Taltal	November 2016	+1.01	+31.90	−0.26	15.72	+30.54	−0.31	−1.32
L.F.P.1.A	Paposo	November 2016	+0.44	+31.31	+0.28	15.26	+31.21	+0.34	−0.10
L.F.P.2.A	Paposo	November 2016	+0.76	+31.64	+0.28	15.26	+31.21	+0.34	−0.42

^a Modern shell samples: Letter A at the end identifies sample obtained at the edge of *F. maxima* shells.Fig. 7. Observed (open dots) versus predicted (dark dots) $\delta^{18}\text{O}_{\text{calcite}}$ values on modern *F. maxima* shells.

situ thermometers ($15.95^\circ\text{C} \pm 1.58$, Table 2), and minimum and maximum mean SST values (20.53 and 22.53°C) fall far outside the instrumental mean SST range (14.25 and 18°C). On the other hand, when SST reconstruction is done with $\delta^{18}\text{O}_{\text{shell}}$ values without the offset correction, shell mean SST ($16.99^\circ\text{C} \pm 2.42$, Table 8) was $\sim 1.04^\circ\text{C}$ warmer than instrumental mean SST (Table 2), minimum and maximum mean SST values (15.82 and 17.93°C) fall within instrumental mean SST range, and shell SST values record the full range of seasonal SST recorded in thermometers (see Max and Min SST values in Table 8). An explanation for the extremely high mean SST of $\delta^{18}\text{O}_{\text{shell}}$ values with

the offset correction may be the low precision of data used in the vital effect calculation. Previous studies have mentioned that the greater the resolved data used for the isotopic composition of the water when calculating predicted $\delta^{18}\text{O}_{\text{shell}}$, the smaller the offset between predicted and measured values (Ferguson et al., 2011; Gutiérrez-Zugasti et al., 2017). As the size of the offset is highly sensitive to $\delta^{18}\text{O}_{\text{seawater}}$ values, our water sampling with only seasonal measurements and the use of $\delta^{18}\text{O}_{\text{seawater}}$ values from November 2015 in the calculation of shells collected during November 2016 (Table 4) may account for a source of error in our vital effect calculation. Also, there are no other isotope studies on *Fissurella* species to compare our offset and evaluate its size and direction. Moreover, the coarse shell sampling resolution used in the study does not provide information on specimen age (ontogenetic effect) or on the time interval included in each shell sample. Consequently, no specific time can be assigned to $\delta^{18}\text{O}_{\text{shell}}$ samples to link them to $\delta^{18}\text{O}_{\text{seawater}}$ signatures and perform an accurate vital effect calculation.

Regarding correlation between instrumental SST and reconstructed values from $\delta^{18}\text{O}_{\text{shell}}$ on modern shells, previous studies have found a closer correspondence between both estimates. These studies have performed oxygen isotope analyses on different mollusc species. For instance, mean SST reconstruction on *Patella vulgata* for the northern coast of Spain yielded values 0.40 – 0.90°C cooler than instrumental records (Gutiérrez-Zugasti et al., 2017). Mean SST from opercula and shell carbonate of *T. sarmaticus* from the coast of South Africa, was also 0.40°C colder than instrumental mean SST (Galimberti et al., 2017). A study on *M. donacium* found a strong correlation between measured SST and shell SST (Carré et al., 2005b). Finally, reconstructed SST for *N. deaurata* and *N. maguellanica* shells from the Beagle Channel showed that shell average SST was around 0.50°C below SST instrumentally recorded from the study area (Colonese et al., 2012). Reconstructed mean SST for *F. maxima* ($\delta^{18}\text{O}_{\text{shell}}$ values without the offset correction)

Table 5

Reported $\delta^{18}\text{O}_{\text{shell/VPDB}}/\text{‰}$ from modern *F. maxima* shells after subtracting $1 \pm 0.5\text{‰}$ to account for the vital effect.^a

Shell ID	Type	Area of collection	Date of collection	N	UTM north	UTM east	$\delta^{18}\text{O}_{\text{VPDB}}/\text{‰}$					
							Mean	Median	Max	Min	S.D.	Var
B.C.2	Modern	Taltal area	November 2015	8	7,200,553	353,748	−0.35	−0.27	+0.03	−1.00	0.36	0.13
B.P6.2	Modern	Taltal area	February 2016	8	7,200,553	353,748	−0.51	−0.50	+0.06	−0.99	0.37	0.14
Z.P6.1	Modern	Paposo area	February 2016	8	7,242,032	346,788	−0.49	−0.51	−0.19	−0.76	0.21	0.04
Z.P6.2	Modern	Paposo area	February 2016	8	7,242,032	346,788	−0.48	−0.45	−0.01	−0.89	0.32	0.10
B.C.P.1	Modern	Taltal area	November 2016	8	7,200,553	353,748	−0.68	−0.80	−0.05	−1.19	0.43	0.18
B.C.P.2	Modern	Taltal area	November 2016	8	7,200,553	353,748	−0.79	−0.90	+0.01	−1.11	0.36	0.13
L.F.P.1	Modern	Paposo area	November 2016	8	7,242,032	346,788	−0.77	−0.80	−0.56	−0.93	0.16	0.03
L.F.P.2	Modern	Paposo area	November 2016	8	7,242,032	346,788	−0.82	−0.81	−0.24	−1.20	0.29	0.08
Total modern							−0.61	−0.68	+0.06	−1.20	0.35	0.12

^a N refers to the number of samples per shell.

Table 6

Reported $\delta^{18}\text{O}_{\text{shell/VPDB}}/\text{‰}$ from modern and archaeological *F. maxima* shells without vital effect correction.^a

Shell ID	Type	Area of collection	Date of collection	N	UTM north	UTM east	$\delta^{18}\text{O}_{\text{VPDB}}/\text{‰}$					
							Mean	Median	Max	Min	S.D.	Var
B.C.2	Modern	Taltal area	November 2015	8	7,200,553	353,748	+0.65	+0.73	+1.03	+0.00	0.36	0.13
B.P6.2	Modern	Taltal area	February 2016	8	7,200,553	353,748	+0.49	+0.50	+1.06	+0.01	0.37	0.14
Z.P6.1	Modern	Paposo area	February 2016	8	7,242,032	346,788	+0.51	+0.49	+0.81	+0.24	0.21	0.04
Z.P6.2	Modern	Paposo area	February 2016	8	7,242,032	346,788	+0.52	+0.55	+0.99	+0.11	0.32	0.10
B.C.P.1	Modern	Taltal area	November 2016	8	7,200,553	353,748	+0.32	+0.20	+0.95	−0.19	0.43	0.18
B.C.P.2	Modern	Taltal area	November 2016	8	7,200,553	353,748	+0.21	+0.10	+1.01	−0.11	0.36	0.13
L.F.P.1	Modern	Paposo area	November 2016	8	7,242,032	346,788	+0.23	+0.20	+0.44	+0.07	0.16	0.03
L.F.P.2	Modern	Paposo area	November 2016	8	7,242,032	346,788	+0.18	+0.19	+0.76	−0.20	0.29	0.08
Total modern							+0.39	+0.32	+1.06	−0.20	0.35	0.12
A.C.1	Archaeological	Site 224A	10,995 cal yr BP	8	7,201,935	354,249	+1.19	+1.17	+1.72	+0.83	0.33	0.11
A.C.2	Archaeological	Site 224A	10,995 cal yr BP	8	7,201,935	354,249	+1.21	+1.18	+1.68	+0.86	0.25	0.06
A.C.3	Archaeological	Site 224A	10,995 cal yr BP	8	7,201,935	354,249	+1.17	+1.24	+1.48	+0.78	0.28	0.08
A.C.4	Archaeological	Site 224A	10,995 cal yr BP	7	7,201,935	354,249	+1.07	+0.94	+1.51	+0.80	0.29	0.08
P.F.1	Archaeological	Site PN9	11,210 cal yr BP	8	7,238,590	350,569	+0.95	+0.84	+1.55	+0.67	0.29	0.08
P.F.2	Archaeological	Site PN9	11,210 cal yr BP	8	7,238,590	350,569	+1.14	+1.09	+1.53	+0.84	0.25	0.06
P.F.3	Archaeological	Site PN9	11,210 cal yr BP	8	7,238,590	350,569	+0.83	+0.77	+1.70	+0.29	0.44	0.20
P.F.4	Archaeological	Site PN9	11,210 cal yr BP	8	7,238,590	350,569	+0.72	+0.70	+1.46	+0.00	0.43	0.19
Total archaeological							+1.03	+1.01	+1.72	+0.00	0.35	0.13

^a N refers to the number of samples per shell.

Table 7

Reconstructed SST (°C) from modern *F. maxima* shells with Vital Effect correction.^a

Shell ID	Type	Site of collection	n	SST (°C)					
				Mean	Median	Max	Min	S.D.	Var
B.C.2	Modern	Taltal area	8	20.35	20.00	23.37	18.64	1.65	2.71
B.P6.2	Modern	Taltal area	8	21.08	21.06	23.31	18.49	1.72	2.95
Z.P6.1	Modern	Paposo area	8	21.01	21.08	22.24	19.61	0.95	0.90
Z.P6.2	Modern	Paposo area	8	20.94	20.81	22.85	18.78	1.49	2.23
B.C.P.1	Modern	Taltal area	8	21.91	22.43	24.29	18.97	1.97	3.89
B.C.P.2	Modern	Taltal area	8	22.40	22.91	23.87	18.71	1.68	2.82
L.F.P.1	Modern	Paposo area	8	22.29	22.43	23.07	21.31	0.74	0.55
L.F.P.2	Modern	Paposo area	8	22.53	22.49	24.32	19.83	1.35	1.82
Total modern				21.56	21.87	24.32	18.49	1.61	2.58

^a N refers to the number of samples per shell.

Table 9

SST (°C) from in situ thermometers, satellite imagery, archaeological *F. maxima* shells and modern *F. maxima* shells.^a

SST (°C)	Thermometers	Satellite	Modern <i>F. maxima</i> Shell	Modern <i>F. maxima</i> shell (co)	Archaeological <i>F. maxima</i> shell
Mean	15.95	16.88	16.99	21.56	14.13
Maximum mean	18.00	20.76	17.93	22.53	15.52
Minimum mean	14.25	14.25	15.82	20.35	13.56
Range	3.75	6.51	2.11	2.18	1.96

^a (co) indicates SST information on corrected $\delta^{18}\text{O}_{\text{shell}}$ values from vital effect.

was ~1.04 °C warmer than instrumental SST, over representing mean water temperature and differing from what has been found for most *Patella* species. One exception is *Patella caerulea* from the

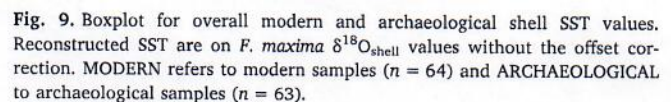
Table 8

Reconstructed SST (°C) from modern and archaeological *F. maxima* shells without vital effect correction.^a

Shell ID	Type	Site of collection	n	SST (°C)					
				Mean	Median	Max	Min	S.D.	Var
B.C.2	Modern	Taltal area	8	15.82	15.49	18.74	14.16	1.59	2.54
B.P6.2	Modern	Taltal area	8	16.53	16.51	18.69	14.03	1.66	2.77
Z.P6.1	Modern	Paposo area	8	16.47	16.53	17.65	15.11	0.92	0.84
Z.P6.2	Modern	Paposo area	8	16.40	16.26	18.25	14.30	1.44	2.09
B.C.P.1	Modern	Taltal area	8	17.33	17.84	19.64	14.49	1.91	3.65
B.C.P.2	Modern	Taltal area	8	17.81	18.30	19.23	14.23	1.63	2.65
L.F.P.1	Modern	Paposo area	8	17.70	17.84	18.45	16.75	0.72	0.51
L.F.P.2	Modern	Paposo area	8	17.93	17.90	19.67	15.32	1.31	1.71
Total modern				16.99	17.29	19.67	14.03	1.55	2.42
A.C.1	Archaeological	Site 224A	8	13.43	13.53	15.01	11.12	1.46	2.14
A.C.2	Archaeological	Site 224A	8	13.36	13.50	14.89	11.29	1.11	1.24
A.C.3	Archaeological	Site 224A	8	13.55	13.24	15.25	12.16	1.23	1.51
A.C.4	Archaeological	Site 224A	7	13.99	14.54	15.16	12.06	1.25	1.56
P.F.1	Archaeological	Site PN9	8	14.51	14.97	15.72	11.89	1.26	1.60
P.F.2	Archaeological	Site PN9	8	13.68	13.88	14.97	11.94	1.08	1.16
P.F.3	Archaeological	Site PN9	8	15.02	15.30	17.42	11.21	1.96	3.82
P.F.4	Archaeological	Site PN9	8	15.52	15.59	18.73	12.25	1.91	3.66
Total archaeological				14.13	14.24	18.73	11.12	1.56	2.44

^a N refers to the number of samples per shell.

Reconstructed SST from modern *F. maxima* shells are different than SST reconstructed from archaeological shells (modern and archaeological $\delta^{18}\text{O}_{\text{shell}}$ values without the offset correction) dated by association to 11,206 and 11,010 cal yr BP (Figs. 8 and 9, Table 8). Early Holocene mean SST (14.13 °C) was cooler than modern temperatures (shell 16.99 °C, thermometer 15.95 °C) (Table 8). This difference implies that Early Holocene mean SST at 25°S was ~2.86 °C cooler than today. This difference between SST estimates based on modern and archaeological shell samples is statistically significant (*t*-test $p < 0.000$, $df = 125$). Considering the temperature error of +1.04 °C, corrected mean SST from modern shells would be 15.95 °C and from



Early Holocene SST reconstructed from archaeological *F. maxima* shells suggests cold SST around the area. Modern conditions associated with nearshore cold waters along the coast of Chile are associated with upwelling activity and entail high primary productivity, the presence of large kelp beds (Vásquez et al., 1998; Villegas et al., 2007) and characteristic associated fauna dominated by benthic species such as herbivorous fishes and a diverse molluscan assemblage (Aldana et al., 2017; Reddin et al., 2015; Wieters, 2005). This scenario is complementary to paleoclimate reconstructions for inland and littoral terrestrial environments that attest to increased local humidity brought about by increased groundwater recharge in inland Andean catchments and/or increased intensity of coastal fog (Díaz et al., 2012; Saez et al.,

2016). The cold and humid climate pattern during the Pleistocene–Holocene transition is detected over much of the Atacama desert and has been attributed to oceanographic and atmospheric anomalies induced by prevailing La Niña-like conditions in the Tropical Pacific (Gayo et al., 2012a, 2012b; Latorre et al., 2002; Maldonado et al., 2005; Quade et al., 2008; Saez et al., 2016).

Early human occupations made use of these favourable environmental conditions, effectively adapting to both highland and coastal ecosystems as early as 11,800 cal yr BP (Cartajena et al., 2014; Grosjean et al., 2005; Latorre et al., 2013; Llagostera, 1992, 2005; Llagostera et al., 2000; Núñez et al., 2002; Salazar et al., 2011, 2017). Marine faunal remains from archaeological sites 224A and Paposo Norte 9 support the scenario of productive habitats along the coast of Taltal. Archaeological fauna assemblages from these sites are characterized by high abundance of different species of the genus *Fissurella* (keyhole limpet), *Acanthopleura echinata* (chiton), *Enoplochiton niger* (chiton), *Tegula atra* (sea snail), and *C. concholepas* shells (Olguín et al., 2015a; Salazar et al., 2017). Regarding fish species, ichthyofaunal records show a predominance of species like *Sciaena deliciosa*, *Cilus gilberti*, *Semicossyphus darwini*, *Scartichthys viridis* and *Trachurus murphyi* (Rebolledo et al., 2016; Salazar et al., 2017), most of them cold water kelp-forest fishes (Berrios and Vargas, 2000; Pérez-Matus et al., 2012). It is interesting to note that archaeological sites from the study area with dates later than 8500 cal yr BP have ichthyofaunal assemblages with higher abundance of warmer water species (Rebolledo et al., 2016). Further studies will be necessary to evaluate the role of paleoceanographic conditions on the composition of fish remains from Middle Holocene archaeological sites of the area of Taltal and the northern coast of Chile.

Our results point to colder than present nearshore conditions during the Early Holocene that are consistent with previous sea temperature reconstructions. Isotope studies ($\delta^{18}\text{O}$) on *C. concholepas* shells from La Chimba-13 archaeological site (23°S) – two degrees of latitude north of our study area and with dates between 10,550 and 9120 cal yr BP – show that coastal SST was around 4 °C cooler than present (Vargas et al., 2006). These similarities coincide with previous interpretations of prevailing cooler SST during the Early Holocene on the coast of southern Peru (18°S) between 9600 and 8900 cal BP (Carré et al., 2005a, 2014).

Reconstructed shell SST from central Chile (31°S) between 10,380 and 9460 cal yr BP have been reported to be similar to modern SST values (Carré et al., 2012). Several explanations have been proposed to interpret higher SST and lower reservoir ages than those obtained in southern Peru and northern Chile (15°S to 23°S) during the Early Holocene (Carré et al., 2016; Fontugne et al., 2004; Orlieb et al., 2011). This Early Holocene latitudinal contrast has been interpreted as the result of differences in the intensity of the upwelling activity along the northern coast (Carré et al., 2005a, 2014; Sadler et al., 2012), a difference in the ^{14}C content of upwelled waters due to their origin (for example higher or lower contribution of sub-Antarctic mode waters (SAMW)) (Fontugne et al., 2004; Hua et al., 2015), and/or the result of changes in the latitudinal character of air-sea CO_2 exchange due to the location of the ESSW–SAMW front somewhere between northern (~18°S) and central Chile (31°S) (Carré et al., 2016).

As deep water brought to the surface by coastal upwelling is characterized by lower temperatures (Aravena et al., 2014; Thiel et al., 2007), Early Holocene cooler SST (Carré et al., 2005a, 2014) and high marine reservoir ages are interpreted as increased upwelling intensity (Carré et al., 2016) on the southern coast of Peru (18°S), which suggests that the cooler than present SST recorded for archaeological shells from sites 224A and Paposo Norte 9 (Taltal, 25°S) and from La Chimba-13 (23°S) may be related to high upwelling activity in the area. More information on reconstructed SST and radiocarbon marine reservoir ages is needed to evaluate and explain changes in paleoceanographic conditions throughout the Holocene along the northern coast of Chile (from 18 to 31°S). Nevertheless, paleo–SST data from archaeological shells of

Taltal contribute to decrease the uncertainty on the spatial organization of paleoceanographic patterns during the Early Holocene. Between around 11,000 and 9000 cal yr BP, the area from southern Peru (18°S) to Taltal (25°S) was characterized by cooler waters and strong upwelling, while the area around Los Vilos (31°S) was dominated by warmer waters and weaker upwelling. These spatial patterns suggest that Early Holocene human occupations of the coast of southern Peru to northern Chile experienced an environment that was distinctively influenced by strong upwelling conditions.

8. Conclusions

In the present study we have provided the first SST record from $\delta^{18}\text{O}$ analyses on modern and archaeological shell carbonates for the coastal Atacama desert (area of Taltal, 25°S). In addition, we have presented the first isotope study on a keyhole limpet species (*F. maxima*) from the Pacific coast of South America, and the first XDR on the composition of calcium carbonate of its shell. Finally, we have calibrated reconstructed SST from modern shells of *F. maxima* with in situ SST measurements for the study area. Mean SST value recorded in thermometers is around 0.93 °C lower than mean SST from satellite information. Therefore, in cases when in situ thermometers are not available to compare with reconstructed shell SST, this offset has to be considered. The reconstructed mean SST obtained from $\delta^{18}\text{O}$ values on calcite outer layers of modern *F. maxima* shells is 1.04 °C warmer than the mean SST from in situ thermometers. Because this temperature offset is predictable and can be taken into account, reconstructed SST from *F. maxima* $\delta^{18}\text{O}_{\text{shell}}$ values can be considered a useful proxy for water temperature, with an approximate error of +1.04 °C. Our results confirm paleoceanographic patterns previously reported for the Early Holocene along South America, with cooler nearshore waters and strong upwelling along the southern coast of Peru and northern Chile. These data are crucial to understand the environmental context of early peopling of the coast of the Atacama desert and South America. Further experimental studies are needed on *F. maxima* shells to assess, for example, the influence of temperature thresholds on its biological processes and during active mineralization. In this regard, sclerochronology studies are needed to identify shell microsample chronology and growth rate of this shellfish species, ubiquitous in shell midden sites along the coast of Chile. Finally, additional studies should be conducted between Taltal (25°S) and Los Vilos (31°S) to identify the past location of the ESSW–SAMW front and therefore understand temporal changes in the structure of the Humboldt Current along the Holocene and their influence on human adaptation through the prehistory of South America.

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