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Groundwater origin and recharge in the hyperarid Cordillera de la Costa, Atacama Desert, northern Chile

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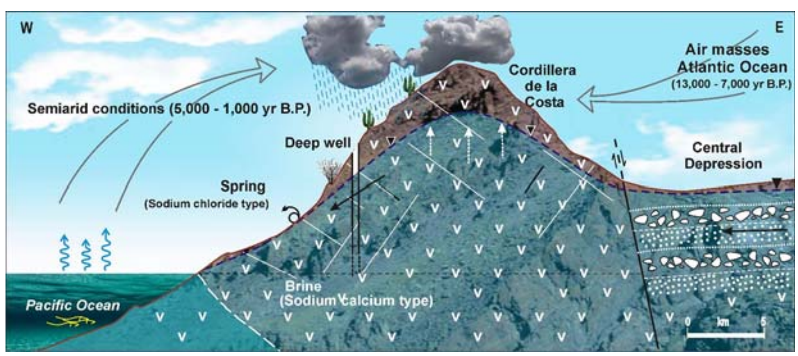
HIGHLIGHTS

- Small springs have been recognized in the hyperarid coastal zone of the Atacama Desert.
- The $\delta^{18}O$ and $\delta^{2}H$ values of spring waters are similar to coastal region rainfall.
- The residence time of the waters from springs varies between 1 and 2 kyr, up to 5 kyr.
- Waters from the deep wells are isotopically much heavier than those of springs.
- Turnover time for deep waters varies between 7 and 13 kyr, which overlaps the CAPE events.

GRAPHICAL ABSTRACT



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ABSTRACT

The Cordillera de la Costa is located along the coastline of northern Chile, in the hyperarid Atacama Desert area. Chemical and isotopic analyses of several small coastal springs and groundwater reservoirs between 22.5 °S and 25.5 °S allow understanding groundwater origin, renewal time and the probable timing of recharge. The aquifers are mostly in old volcanic rocks and alluvial deposits. All spring waters are brackish, of the sodium chloride type due to intensive concentration of precipitation due aridity and for deep groundwater to additional water-rock interaction in slowly renewed groundwater and mixing with deep seated brines. The heavy $\delta^{18}O$ and $\delta^{2}H$ values in spring water are explained by recharge by the arrival of moist air masses from the Pacific Ocean and the originally lighter values in the deep wells can be associated to past recharge by air masses coming from the Atlantic Ocean. Current recharge is assumed almost nil but it was significant in past wetter-than-present periods, increasing groundwater reserves, which are not yet exhausted. To explain the observed chloride content and radiocarbon (^{14}C) activity, a well-mixed (exponential) flow model has been considered for aquifer recharge. The average residence time of groundwater feeding the springs has been estimated between 1 and 2 kyr, up to 5 kyr and between 7 and 13 kyr for deep well water, assuming that current recharge is much less than during the previous wetter period. The recharge period feeding the coastal springs could have been produced 1 to 5 kyr BP, when the area

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was already inhabited, and recharge in the Michilla mine was produced during the 10 to 14.5 kyr BP CAPE (Central Andean Pluvial Event) pluvial events of the central Andes. The approximate coincidence of turnover time with the past wet periods, as revealed by paleoclimate data, points to significant recharge during them.

1. Introduction

Coastal aquifers in northern Chile provide a unique opportunity to understand climate variability in the currently hyper-arid Atacama Desert. The Atacama is one of the driest places on Earth (Hartley and Chong, 2002). The average long-term precipitation is <1 mm/yr in some areas. Nevertheless, localized coastal storms can occur with a 15–20 year recurrence interval which may locally exceed 20 mm per event (Vargas et al., 2000). The large rare storms generate ephemeral surface runoff and small endorheic lagoons, which can produce concentrated recharge in certain areas of the Cordillera de la Costa.

The climate history during the Late Quaternary in northern Chile is complex. According to sedimentary records from various areas of the Atacama Desert, since the onset of hyper-arid conditions in the Middle Miocene the climate was characterized by an alternation of arid and less arid periods (Vargas et al., 2000, 2006; Rech et al., 2006; Jordan et al., 2014). Infrequent and high-intensity storm events, with recurrence intervals of decades (e.g. the ENSO, El Niño–Southern Oscillation phenomena) or centuries (changes in solar and cosmic-ray activity or millennial orbital forcing), could enable significant recharge in brief periods of time. Recent storms such as that in March 2015 over coastal northern Chile (Jordan et al., 2015; Bozkurt et al., 2016; Wilcox et al., 2016), with catastrophic consequences for urban population, serve as examples. This storm was triggered in part by the 2015/2016 El Niño warm event and also affected a broad interior area. The March 2015 storm produced recharge in the southern Atacama Desert (Salas et al., 2016). Another major storm occurred in June 2017. During these two rare events, 20 and 21 mm of rain fell, respectively, in the coastal city of Antofagasta.

Given evidence from sedimentary and midden records for several “less dry” periods during the last 14.5 kyr, it is hypothesized that during some of these less-dry periods the increased frequency of high-intensity storm events led to the main recharge of aquifers in many parts of the Atacama. The moisture sources that fed the wetter-than-present periods of the interior regions are assumed to be the consequence of changes in summer NE and SE atmospheric regimes, which transport humidity from the Atlantic through the Amazonian basin (NE) and the Chaco region (SE) (Aravena et al., 1999). Higher groundwater levels expressed by high stands of lake levels in western Andean Miscanti and Lejía lakes at 23°–24 °S (Grosjean et al., 2003), by groundwater discharge deposits in the Precordillera at 24°–26°S (Quade et al., 2008; Sáez et al., 2016), and by aggraded terraces in Sierra Moreno, in the eastern Atacama Desert around 21 °S (Gayo et al., 2012a, 2012b), point to the existence of those enhanced eastern moisture sources.

Sources of moisture from Pacific Ocean to northern Chile have also been proposed. Herrera and Custodio (2014a) presented evidence that the water from some small coastal springs near the city of Antofagasta originated from Pacific moisture and was probably recharged between 3 and 5 kyr BP, as a consequence of ENSO forcing (El Niño – Southern Oscillation). A Westerlies Pacific moisture source was also suggested by Grosjean et al. (1997a, 1997b) for the Negro Francisco Andean lake at the south end of the Atacama Desert (27 °S), during the last 5 kyr.

Due to the scarcity of sedimentological and paleobotanical paleoclimate records at key latitudes along the coastal fringe of the Atacama Desert, doubts arise about the spatial and temporal variability of paleoclimate and its causes. To try to overcome this situation, groundwater chemistry and environmental isotopes could provide proxies to understand and determine the effects of paleoclimate events. To that end, the main objective of this investigation is to contribute to the understanding of the origin and timing of recharge of the water stored in aquifers in the Cordillera de la Costa by means of chemical and environmental stable and radioactive isotopes.

2. Cordillera de la Costa setting

2.1. Relief and climate

The Cordillera de la Costa (Coastal Range) is an N—S oriented morpho-structural unit, 2000 km long, from 18°S to 38°S, 10–40 km wide, with an average elevation of 1000 m and topping at 2000 m (Fig. 1). In the considered area, the Cordillera de la Costa is bounded to the east by the Central Depression, which is filled by Cenozoic deposits (Sáez et al., 1999). The Cordillera de la Costa is a mountainous barrier to the westward flow toward the ocean of groundwater from the Precordillera and the wetter Altiplano areas. Most groundwater coming from the eastern highlands evaporates in the intermediate depressions, forming large salares (salt pans). This causes the groundwater east of the Atacama Fault (Fig. 2) to have a different composition than groundwater to the west of this important crustal feature.

The northern sector of the Cordillera de la Costa, between 18 °S to 26 °S, is part of the hyper-arid Atacama Desert, which spans from the western foothills of the Andes to the coast. The hyper-aridity is a consequence of three factors: a) the presence of the Cordillera de los Andes (Andes Range) and the Altiplano, which act as a high elevation physical barrier that blocks moisture from the Atlantic, b) the Humboldt ocean current, whose cold water hinders the production of Pacific moisture, causes an atmospheric inversion and also modulates the strength of the Pacific anticyclone (Garreaud et al., 2010), and c) the fact that the westerlies, which transport Pacific moisture to southern Chile, commonly produce precipitation only as far north as 30 °S latitude (Sáez et al., 2016). The sector of the Cordillera de la Costa investigated here, between 22.5 °S and 25.5 °S, receives average precipitation of <4 mm/yr (DGA, 2009), most of it during the austral winter (Houston, 2006). However, in El Niño years, when the probability of extreme precipitation events associated with an increase of ocean surface temperature in the tropics increases, the rainfall may reach 10 mm/yr along the coast (Garreaud, 2009).

Persistent fog (*camanchaca*) in the winter months is common on the ocean side of the Cordillera de la Costa. This is the consequence of low elevation stratocumulus clouds beneath a persistent temperature inversion (Cereceda et al., 2002, 2008a). The contribution of this fog to recharge in the considered area is probably nil, based on observations near Antofagasta. There, the cloud base is above land level, although some local contribution to recharge could be produced in higher areas, such as Cuncun, Panul, Perales and sites near Taltal. Isotopic studies of rainfall in central-northern Chile indicate that this type of drizzle does not produce significant recharge to aquifers, although it favors the development of vegetation (Aravena et al., 1989; Squeo et al., 2006). The fog rarely reaches the Central Depression, as the high ranges of the Cordillera de la Costa act as a barrier, except where there are wide canyons across it, like the Loa river valley (Rech et al., 2003; Cereceda et al., 2008b).

The temperature remains relatively stable during the year, with monthly average values ranging between 13.5 °C and 20.1 °C (DGA, 2009).

2.2. Geological and hydrogeological setting

The Cordillera de la Costa corresponds to the Upper Jurassic–lower Upper Cretaceous Volcanic arc related to subduction of the Nazca plate beneath South America (Fig. 2). The Jurassic–Cretaceous volcanic