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OXYGEN AND HYDROGEN STABLE ISOTOPE MAPS FOR METEORIC GROUNDWATER IN COSTA RICA, EXCLUDING GEOTHERMAL WATERS

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We present a set of maps showing the distribution of oxygen and hydrogen isotope values, relative to the VSMOW standard, for the nation of Costa Rica. These maps utilize data from this study (51 new data points; 21 wells, 16 rivers, 14 springs) and data from previous workers (51 data points for rivers, Lachniet and Patterson, 2002; 13 data points for springs, Darling et al., 1989). Computer generated spherical kriging with a 12-point variable was used to produce interpolated isotope contours for each map. An altitude effect of 1.5 to 3 per mil was observed locally, with a superimposed decrease in $\delta^{18}O$ *with decreasing latitude for low elevation locations. Additional work along the northern border with Nicaragua, in the northern Nicoya Peninsula, and the southern Cordillera de Talamanca will be required to produce a more complete map. Potential collaborators wishing to provide samples or data from these areas should contact the authors. This map will be updated as new data is added, and posted on the internet at http://wri.csusb.edu/.*

INTRODUCTION

Stable isotope data for groundwater are important for understanding groundwater flow, surface-groundwater interaction, spring and groundwater recharge, and for interpretation of paleoclimate information. Oxygen and hydrogen isotope data for groundwater in Central America, and studies which examine stable isotope distribution in the tropics are scarce (e.g., Payne and Yurtsever, 1974; Darling et al., 1989; Salati et al., 1979; Gonfiantini et al., 1976; Longinelli and Edmond, 1983; Gat and Matsui, 1991; Njitchoua et al., 1999; Lachniet and Patterson, 2002; Lachniet and Patterson, 2006; Poveda et al., 2006). Studies in Costa Rica have focused dominantly upon water as a resource (e.g., Sanabria, 2001), surface waters (Lachniet and Patterson, 2002, Lachniet et al., 2007), or hydrothermally modified waters from volcanic aquifers (Darling et al., 1989; Pringle et al., 1990; Pringle, 1991; Genereux and Pringle, 1997; Birkle and Bundschuh, 2007). This lack of data for stable isotope distribution of groundwaters in Costa Rica has restricted their use in both groundwater and paleoclimate studies.

Precipitation

Limited stable isotope data on precipitation are available for Costa Rica (e.g., IAEA/WMO, 1998; Lachniet and Patterson, 2002). Shortcomings of these data include spatial bias to northwestern Costa Rica, limited temporal spread dominated by the period 1990-3, and limited accompanying data for temperature and precipitation amount. However, the data demonstrate that isotope values of precipitation yield a water line equation ($\delta D = 7.8 \times \delta^{18}O + 7.9$; Lachniet and Patterson, 2002) that is similar to the global meteoric water line ($\delta D = 8 \times \delta^{18}O + 10$; Craig, 1961), and that precipitation is seasonably variable (Lachniet and Patterson, 2002). Correlation of these data with elevation for the Caribbean slope and central highlands of Costa Rica indicates a $\delta^{18}O$ value decrease of –1.9‰ per kilometer of elevation (Lachniet and Patterson, 2002), which is comparable to values reported elsewhere in the tropics and North America (e.g., Payne and Yurtsever, 1974; Rozanski et al., 1993; Rose et al., 1996; Melchiorre et al., 1999).

Surface Waters

Stable isotope data for surface waters of Costa Rica are available in Darling et al. (1989), and Lachniet and Patterson (2002). The nine isotope analyses of river water presented in Darling et al. (1989) provide only generalized sampling locations (e.g., "Rio Seca"), and are from areas where volcanic-related hydrothermal activity may significantly modify waters. Of the 63 river and lake samples reported in Lachniet and Patterson (2002), 12 are from lakes or marshes where evaporative modification may have altered isotope values. Despite these shortcomings and limited coverage in some parts of Costa Rica, Lachniet and Patterson (2002) present reliable and detailed $\delta^{18}O$ and δD maps of surface waters.

Volcanic Aquifers and Geothermal Waters

There is evidence that groundwater in portions of the Costa Rican Valle Central receive a significant quantity of recharge from a hydrothermally altered source, based upon positive $\delta^{18}O$ deviation from the local meteoric water line and deviation from local $\delta^{18}O$ vs. elevation relations (Darling et al., 1989). Additionally, geochemical studies suggest that some groundwater of the Costa Rican Caribbean slope contain locally significant quantities of geothermally modified waters (Pringle et al., 1990; Pringle, 1991; Genereux and Pringle, 1997). The isotope values of these modified waters are interpreted in this study as not representative of meteoric groundwater.

Objectives of this Study

We examine the $\delta^{18}O$ and δD values of springs, wells, and gaining (baseflow-fed) rivers to produce maps that show the observed spatial distribution of stable isotope values for Costa Rican groundwater. We also examine the $\delta^{18}O$ vs. elevation gradient in both the Caribbean Monte Verde area and Pacific Osa Peninsula. The isotope values of meteoric water, surface runoff, shallow recharge springs, and geothermal waters are beyond the scope of this study and therefore not presented in this paper. These maps are intended to assist with future paleoclimate, volcanology, and hydrology studies in Costa Rica.

METHODS

Our river sampling focused upon sections believed to represent gaining, or groundwater base-flow fed rivers. Abrupt temperature change and/or upwelling flow indicative of significant localized base flow recharge were used as qualitative indicators for the identification of such sections. Water samples for isotope analysis were collected in a borosilicate glass bottle with a polyseal cap. Water samples were prepared for isotope analyses using the standard CO_2 equilibration method for oxygen isotopes (Epstein and Mayeda 1953), and by hydrogen gas equilibration for hydrogen isotopes (e.g., Horita, 1988). Isotope values were measured using an automated sample equilibrator interfaced with a Finnigan Delta Plus Advantage gas ratio mass spectrometer at California State University, San Bernardino. Results are reported in the usual d notation relative to Vienna Standard Mean Ocean Water (VSMOW) (Coplen 1995). Laboratory precision is ±0.08‰ for oxygen and ±1.2‰ for hydrogen isotope values, based on duplicate analyses of internal laboratory standards. Eight waters where both the $\delta^{18}O$ and δD values plot significantly off the global meteoric water line (Craig, 1961), and possessing unusual chemistry such as extremely elevated TDS were assumed to be modified (e.g., anthropogenic, hydrothermal) and were not used in this study.

The isotope maps were generated using available data for groundwater, springs, and rivers with a significant groundwater base flow component. Interpolated contouring of this data using ARC-INFO Geographic Information Software was performed using spherical kriging, with a 12-point variable. This method and attendant conditions are described in McBratney and Webster (1986). Variance was calculated using the average variance of all point pairs within each interval of the cell size. This variogram is then automatically fit to the variance points using the Levenberg-Marquardt Method (Press et al., 1986) of nonlinear least squares approximation.

RESULTS AND DISCUSSION

We collected and analyzed water from 21 wells, 16 gaining rivers, and 14 springs at elevations ranging from 10 to 2994 meters above sea level (Figure 1, Table 1). Measured $\delta^{18}O$ values of waters range from –12.9 to –3.2‰ while δD values range from –84 to –14‰.

This study also utilizes isotope data for 51 rivers presented in Lachniet and Patterson (2002). The degree of base flow at sampling points for these rivers could not be determined for many locations. However, the general consistency of these surface water data with our groundwater data, as plotted in Figure 4 suggests a significant degree of surface-groundwater interaction across Costa Rica. This is consistent with our observations that most rivers in Costa Rica, with the exception of some in semi-arid portions of the northwest, have significant base flow. Spatial and temporal concordance between our data and the data from Lachniet and Patterson (2002) also

Table 1. Sample locations and the $\delta^{18}O$ and δD (SMOW) values for meteoric waters of Costa Rica.

Sample #	Sample Name	Sample Type	Sample Date	Northing	Westing	Elevation (meters)	$\delta^{18}O$ (VSMOW)	δD (VSMOW)
1	Cano Palma Well	Well	22-Dec-01	10º 35.618'	83º 31.650'	10	-3.20	-14
2	Jaco Well	Well	29-Dec-01	09º 37.291'	84º 38.070'	12	-7.68	-49
3	Rio Puerto Viejo at La Selva	River	25-Dec-01	10º 25.882'	84º 00.309'	15	-4.34	-22
4	Quepos Well	Well	2-Jan-02	09º 27.347'	84º 09.000'	18	-7.45	-45
5	Rio Blanco at Hyw 1	River	28-Dec-01	10º 28.358'	85º 10.809'	20	-5.95	-35
6	Rio Suerte at Bannana Boat Stop	River	22-Dec-01	10º 31.501'	83º 37.755'	21	-3.83	-17
7	Rio Peje at La Selva	River	24-Dec-01	10º 25.926'	84º 01.556'	21	-5.24	-17
8	Campanario Station Springbox	Spring	31-Dec-01	08º 38.553'	83º 43.530'	22	-7.35	-45
9	Puerto Viejo Well	Well	3-Jan-02	09º 39.679'	82º 46.911'	22	-5.63	-34
10	Sierpe River at Sierpe	River	2-Jan-02	08º 51.598'	83º 28.289'	24	-8.14	-51
11	Sierpe Town Well	Well	30-Dec-01	08º 51.601'	83º 28.299'	27	-8.01	-52
12	Rio Terrabe at Palmar Norte	River	2-Jan-02	08º 57.506'	83º 27.501'	31	-8.25	-52
13	Rio Suerte at La Suerte Station	River	27-Dec-01	10º 26.734'	83º 47.194'	32	-5.07	-27
14	Rio Tarcoles Well at Los Crocodrilos	River	29-Dec-01	09º 48.100'	84º 36.406'	33	-7.49	-44
15	Loma Well	Well	29-Dec-01	09º 32.707'	84º 23.422'	34	-7.29	-44
16	Dominical Well at Dominical	Well	2-Jan-02	09º 15.414'	83º 51.762'	37	-7.28	-43
17	Cariari Well	Well	26-Dec-01	10º 23.011'	83º 46.899'	38	-4.19	-24
18	La Suerte Station well (12m deep)	Well	27-Dec-01	10º 26.312'	83º 47.165'	41	-4.02	-18
19	La Selva Well (30m deep)	Well	25-Dec-01	10º 25.880'	84º 00.170'	48	-3.59	-16
20	Siquirres Well	Well	26-Dec-01	10º 06.140'	83º 31.190'	91	-5.16	-27
21	Bratsi Well	Well	3-Jan-02	09º 33.899'	82º 53.662'	92	-6.22	-38
22	Rio Lari	River	3-Jan-02	09º 31.725'	82º 58.214'	104	-6.97	-47
23	Rio Lagarto at Hyw 1 near Yomale	River	15-Dec-01	10º 09.989'	84º 54.856'	118	-8.37	-51
24	Liberia Well	Well	28-Dec-01	10º 37.289'	85º 26.393'	147	-6.09	-37
25	Las Juntas Well	Well	15-Dec-01	10º 17.152'	84º 57.525'	150	-7.88	-50
26	Rio Agujas Spring	Spring	1-Jan-02	08º 39.013'	83º 40.331'	182	-8.07	-50
27	Ganado Spring	Spring	2-Jan-02	08º 43.162'	83º 35.813'	301	-8.20	-52
28	Santa Rosa Park Well	Well	29-Dec-01	10º 50.370'	85º 37.092'	312	-7.19	-42
29	Potrero Grande Well	Well	2-Jan-02	09º 01.000'	83º 11.000'	320	-9.75	-61
30	Rio San Juan at Angeles	River	16-Dec-01	10º 16.217'	84º 54.031'	342	-8.51	-54
31	Rio Sucio at Hyw 32 bridge	River	22-Dec-01	10º 08.840'	83º 56.777'	360	-5.88	-34
32	Guancimal River at Bridge	River	20-Dec-01	10º 12.983'	84º 51.048'	480	-7.22	-41
33	Madre Maria Spring, near las Juntas	Spring	16-Dec-01	10º 15.989'	84º 52.421'	490	-8.73	-55
34	Cerro Brujo Spring	Spring	1-Jan-02	08º 39.641'	83º 36.628'	498	-8.53	-53
35	Spring above Dos Brazos	Spring	1-Jan-02	08º 32.091'	83º 29.348'	610	-8.58	-55
36	Well at Tinamase	Well	30-Dec-01	09º 17.317'	83º 47.473'	616	-8.56	-54
37	San Isidro General, Well	Well	2-Jan-02	09º 02.010'	83º 20.090'	803	-9.62	-61
38	Rio Penas Blancas at "the Germans"	River	18-Dec-01	10º 17.893'	84º 44.419'	891	-5.97	-36
39	Palmares Well	Well	15-Dec-01	10º 03.420'	84º 26.050'	992	-9.65	-62
40	Grecia Spring at Atenas	Spring	15-Dec-01	10º 04.006'	84º 19.000'	1002	-9.77	-65
41	San Vito Well	Well	2-Jan-02	08º 50.000'	82º 58.000'	1050	-9.32	-60
42	Monteverde #1	Spring	18-Dec-01	10º 17.859'	84º 45.813'	1140	-6.66	-44
43	Monteverde #2	Spring	18-Dec-01	10º 17.924'	84º 45.998'	1160	-6.87	-45
44	Monteverde #3	Spring	18-Dec-01	10º 17.899'	84º 46.251'	1220	-7.13	-44
45	Big Creek, Monteverde	River	20-Dec-01	10º 18.586'	84º 48.711'	1403	-7.02	-45
46	Cheese Factory Creek, Monteverde	River	20-Dec-01	10º 18.279'	84º 48.538'	1404	-7.05	-43
47	Tunnel Spring, Hyw 32 at Zurque Peak	Spring	28-Dec-01	10º 04.018'	84º 00.322'	1523	-7.90	-50
48	AyA Spring, Monteverde	Spring	20-Dec-01	10º 17.997'	84º 48.339'	1546	-7.95	-54
49	Monteverde #4	Spring	18-Dec-01	10º 18.166'	84º 47.002'	1580	-8.51	-59
50	Villa Mills Well	Well	2-Jan-02	09º 20.785'	83º 20.129'	2909	-12.52	-83
51	AyA Spring at Hyw 2 marker 96	Spring	2-Jan-02	09º 33.627'	83º 42.481'	2994	-12.92	-84

Figure 1. Location of water samples used in this study.

Figure 1 (continued). Location of water samples used in this study.

suggest that these samples represent meteoric waters and not waters modified significantly by hydrothermal activity. For these reasons, we use the data from Lachniet and Patterson (2002) in our generation of the isotope value maps of Costa Rica.

We also utilize data for 13 springs from Darling et al. (1989). We omit the data for other additional springs which the authors of that study suggested contain modified geothermal waters, or which differ significantly from the global meteoric water line. The well isotope data from Darling et al. (1989) is not utilized, as specific well locations are not recorded.

Distribution of $\delta^{18}O$ and δD Values

Oxygen and hydrogen isotope data for a combined total of 115 unique ground and baseflow-fed surface water locations (Figure 1) from this study and other sources (Darling et al., 1989; Lachniet and Patterson, 2002) were compiled and contoured to show distribution across Costa Rica (Figures 2 and 3). Groundwater isotope values exhibit spatial variation with respect to elevation, similar to the effect observed for waters in other locations around the world (e.g., California, Melchiorre et al., 1999; Panama, Lachniet and Patterson, 2006). Additionally, low elevation coastal areas exhibit a correlation with latitude, with lower values generally to the south, and higher values to the north. As expected, the meteoric water line for groundwater of Costa Rica ($\delta D = 7.7\delta^{18}O + 11.1$; Figure 4) is quite close to the global meteoric water line ($\delta D = 8\delta^{18}O + 10$) of Craig (1961).

One significant anomaly occurs in the mapped $\delta^{18}O$ values of north central Costa Rica around Canas (Figure 2). In this area, there is an unexplained increase in $\delta^{18}O$ values. It is most likely that this unusual zone of higher $\delta^{18}O$ values is an artifact of low sample frequency in the area, and that the higher $\delta^{18}O$ values are connected to a similar coastal zone. Only additional sampling in this rugged and remote portion of Costa Rica will resolve this issue. No similar effect is observed for δD values, due to the resolution of the selected contour interval.

Factors Controlling $\delta^{18}O$ and δD Values

• Effect of Elevation Upon $\delta^{18}O$ Values

Examination of the relationship between $\delta^{18}O$ values and elevation at corresponding sampling sites (Figure 5) shows a correlation with R=0.63. Close examination reveals that deviations from this $\delta^{18}O$ vs. elevation trend result from two mechanisms. The first is local elevation effect which produces locally different $\delta^{18}O$ – elevation correlations with different Y-intercept and slope values. The second is a latitude-dependent effect for coastal sites at low elevation.

Local variation in orographic isotope fractionation of precipitation-derived groundwater is not unexpected. The Pacific coast has a wet season between May and October in the north and April to December in the south. The precipitation of the wet season is fed by thermal convection and onshore breezes. The Caribbean coast receives ample year-round precipitation due to northeasterly trade winds. (National Oceanic and Atmospheric Administration, 2008; Poveda et al., 2006). On the Pacific coast, data from the Osa peninsula defines a $\delta^{18}O$ decrease of 1.5‰ per 1000 meters of elevation increase (Figure 6a); on the Caribbean coast, the data from the Monteverde/Rio Peñas Blancas Valley defines a $\delta^{18}O$ decrease of 3.0‰ per 1000 meters of elevation increase (Figure 6b). The difference in intensity of elevation-induced fractionation between the two coasts is believed to be controlled by differences in the respective climate patterns and oceanic temperatures, with localized influence from baseflow recharge elevation and specific humidity (e.g., Gonfiantini

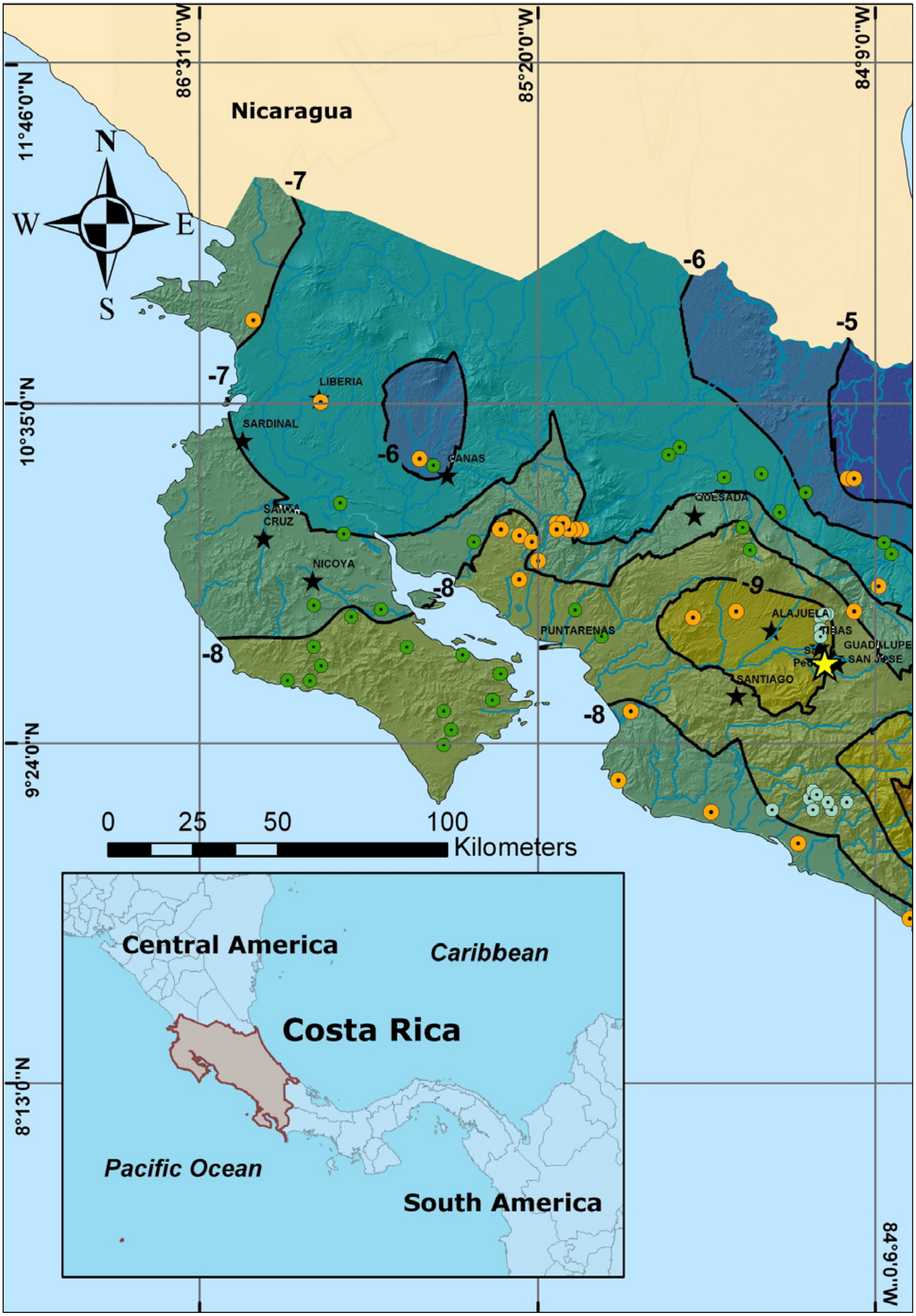

Figure 2. δ[18]O(VSMOW) values of groundwater in Costa Rica.

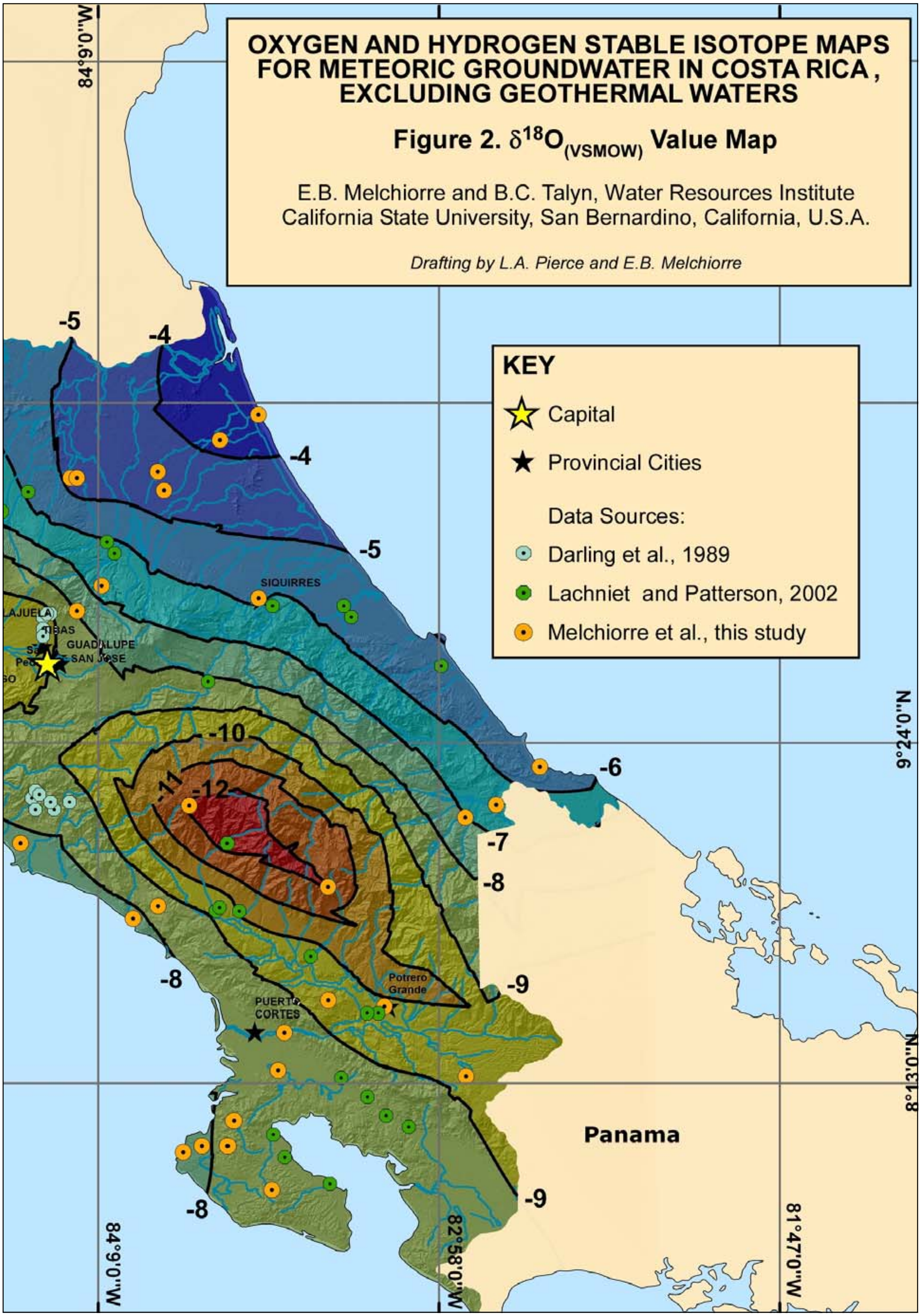

Figure 2 (continued). $\delta^{18}O$(VSMOW) values of groundwater in Costa Rica.

Figure 3. δD(VSMOW) values of groundwater in Costa Rica.

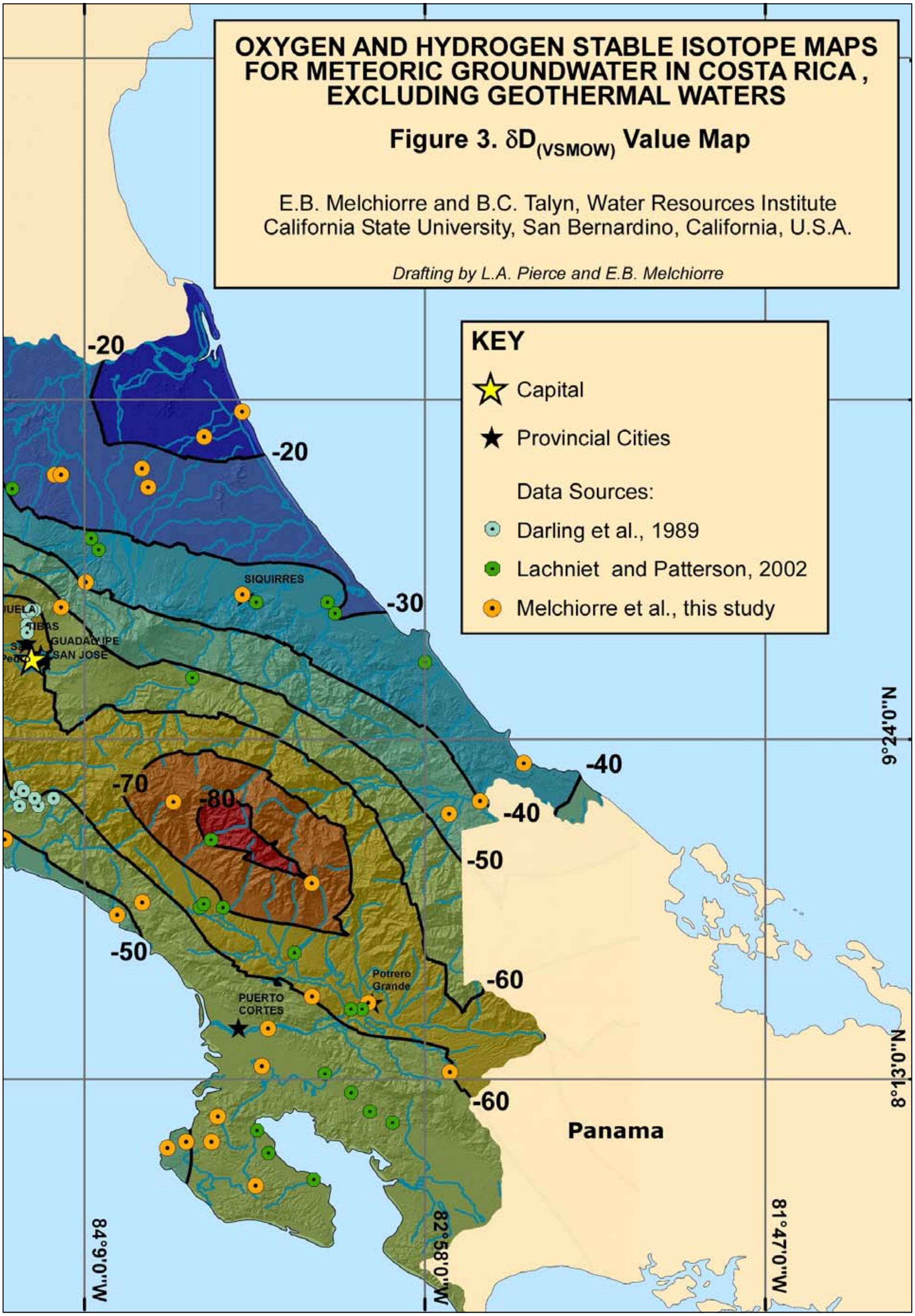

Figure 3 (continued). δ^{18}D(VSMOW) values of groundwater in Costa Rica.

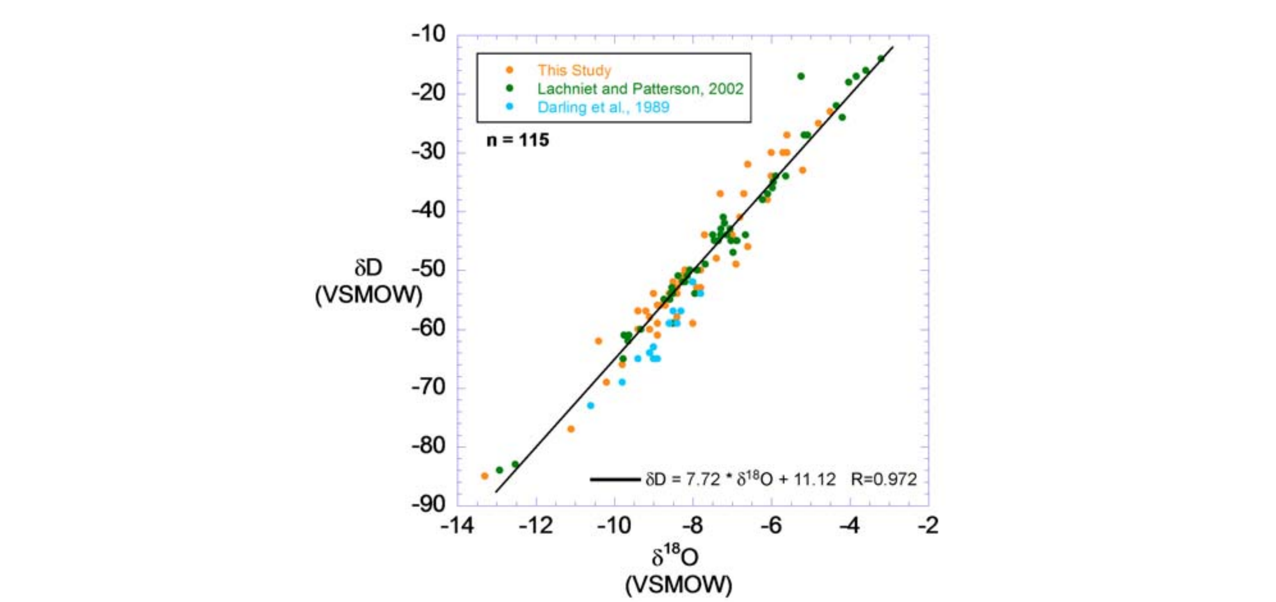

Figure 4. δ^{18}O(VSMOW) vs. δD(VSMOW) plot for samples used in this study.

et al., 2001; Blisniuk and Stern, 2005). These variations make it difficult to describe a generalized trend of δ^{18}O change with respect to elevation which would hold true for the entire nation of Costa Rica.

• Effect of Latitude Upon δ^{18}O Values

Groundwater samples from this study, with low elevations of <100 m above sea level, show strong correlation (r=0.7) between δ^{18}O and latitude, with an observed decrease in δ^{18}O with decreasing latitude (Figure 7). Correlation between δ^{18}O and latitude (r=0.71) was also observed for surface water samples in the neighboring nation of Panama (Lachniet and Patterson, 2006), though this study compared samples from all elevations. Our re-examination of the data for Panama from Lachniet and Patterson (2006) shows that for all samples <100 m above sea level there is actually a stronger correlation (r=0.79). Furthermore, the observed decrease in δ^{18}O with decreasing latitude for our Costa Rica data are of a similar slope and y-intercept as the Panama data.

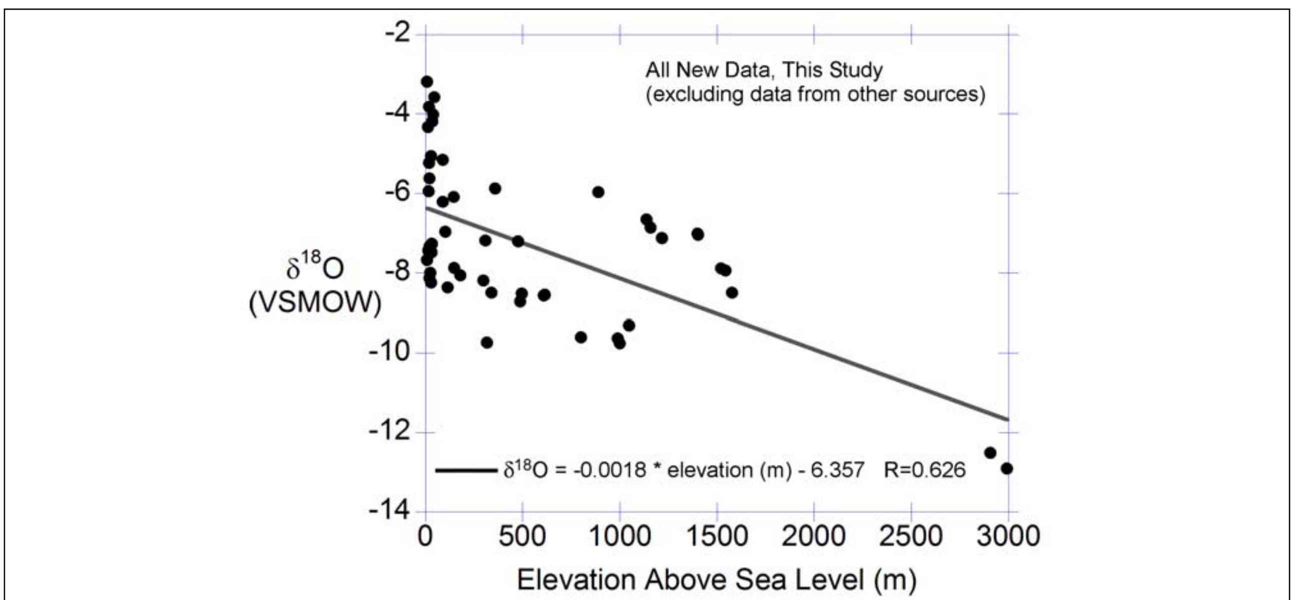

Figure 5. δ^{18}O(VSMOW) vs. elevation for samples used in this study.

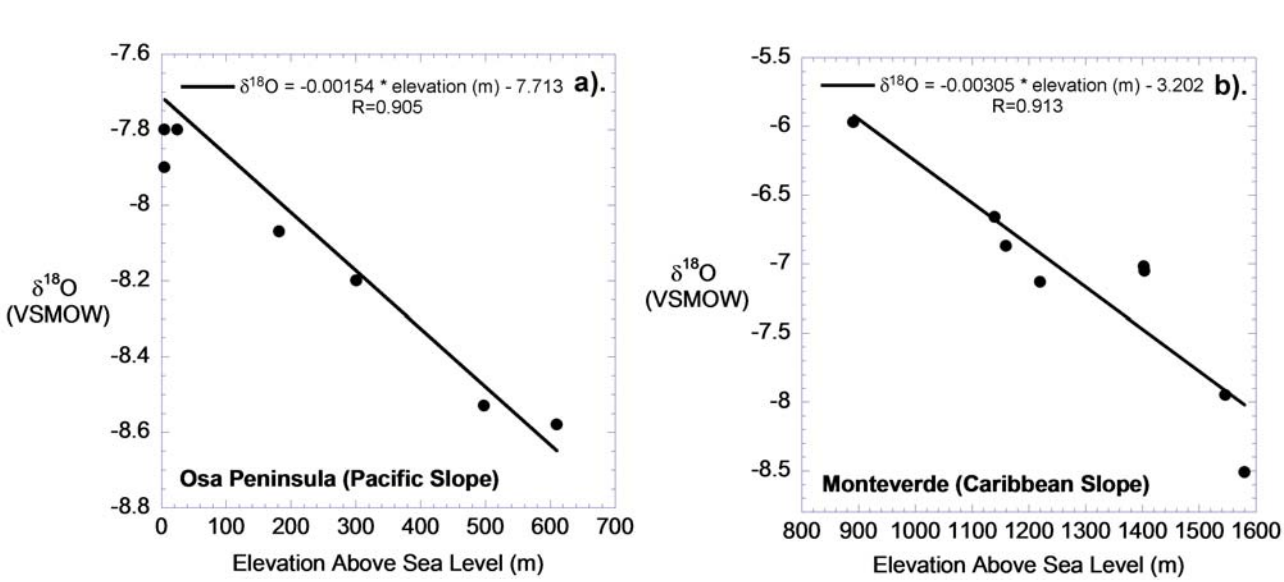

Figure 6. $\delta^{18}O$(VSMOW) vs. elevation for samples from a) the Osa Peninsula and b) Monteverde area.

Other previous research has noted this type of effect in the humid tropics (e.g., Vuille and Werner, 2005, Lachniet et al., 2007). Our observed decrease in $\delta^{18}O$ with decreasing latitude is the inverse of the temperature-dependant latitude effect observed for the United States (Kendall and Coplen, 2001). It is believed that this latitude effect results from a trade wind signal, with increasing Rayleigh distillation as air masses traverse the isthmus (Lachniet et al., 2007). In Costa Rica, the trade wind vector is highly correlated with latitude (Hofmann et al., 1981), with the high mountains of the Cordillera de Talamanca superimposing a low $\delta^{18}O$ signature to vapor and precipitation in southern Costa Rica. This enhanced orographic distillation results in low $\delta^{18}O$ vapor being advected to the Pacific Coast (Lachniet et al., 2007). The paleoclimate record of stalagmites from the Panamanian isthmus also records this effect (Lachniet et al., 2007).

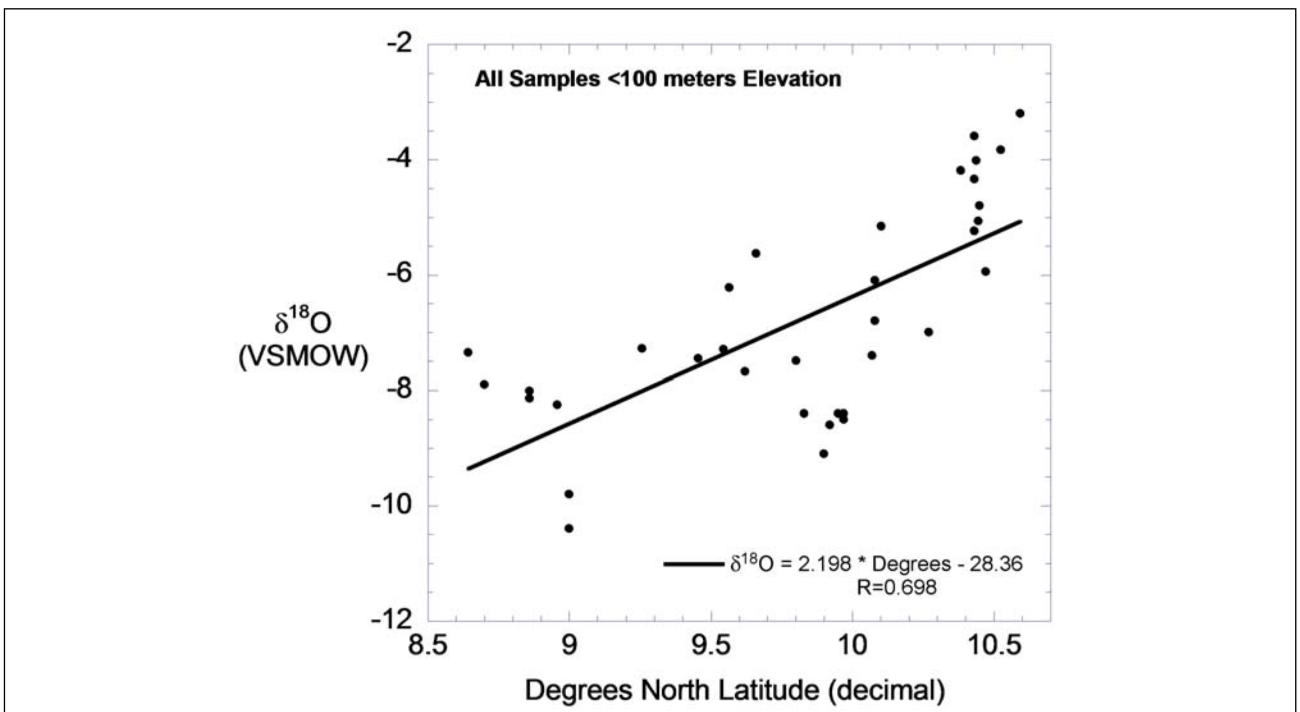

Figure 7. $\delta^{18}O$(VSMOW) vs. latitude for samples with elevation <100m used in this study.

CONCLUSIONS

The new and historical isotopic data for groundwater of Costa Rica have been used to generate preliminary maps of $\delta^{18}O$ and δD values across this nation. New data will be added in the future to this data set and these maps will be updated and re-posted in an on-line format at: http://wri.csusb.edu/. Though the isotopic compositions are predictably lower at higher elevations, quantification of this regionally-variable effect is only possible in localized, coastal-specific areas. For low elevation samples (<100m), a decrease in isotope values is observed with decreasing latitude.

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