# A non-linear inverse technique for calculating palaeotemperature and other variables using noble gas concentrations in groundwater: The Last Glacial Maximum in the continental tropics re-examined

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We present here an error weighted non-linear inverse technique adapted from Menke (1984). This method fits palaeotemperature and up to two other variables, gives an estimate of the precision of the fitted variables and enables us to assess the confidence of the conceptual models with the input data. We illustrate the utility of this method with comprehensive data sets from the Pannonian basin, San Juan basin and tropical Brazil (Stute and Deak, 1989; Stute *et al.*, 1995a,b). Solving for temperature and 'excess air' we demonstrate that the inverse method reproduces literature iterative techniques, but with a bias of up to 1.0°C. This is due to error weighting placing more emphasis on the heavy noble gas concentrations in the temperature determination. Solving for either recharge salinity or altitude as a third variable, synthetic data sets reproduce input values. All the literature data produces a significant average negative offset from known recharge salinity and altitude. This offset in natural systems points to a significant and ubiquitous noble gas fractionation effect in all of the aquifer systems investigated.

We also solve for fractionation by diffusive gas loss at recharge (Stute *et al.*, 1995b). The tropical Brazil data set reproduces independently derived literature fractionation constants. Although this improves the data fit, a simple statistical test shows that diffusive fractionation alone cannot account for the sample noble gas abundance pattern observed in the tropical Brazil samples. Our derived errors of between $\pm 1.6$ to $\pm 6.3$°C ($1\sigma$) are significantly higher than the quoted literature error of $\pm 0.8$°C. This is due to both the inclusion of the third variable and the poor fit of the sample data to the conceptual model. When solving for fractionation in the Pannonian basin and San Juan data, we demonstrate that optimal recharge salinity for the combined data is now within error of meteoric water (Fig. 1). Palaeotemperature errors range between $\pm 0.4$ to $\pm 2.5$°C and $\pm 0.8$ to $\pm 2.4$°C respectively. In both cases the data show a significant degree of improvement in the fit of the data to the model, the conceptual model is statistically consistent with both data sets, young samples are within error of the current day recharge temperatures, and samples previously considered outliers now agree with samples in the same age bracket. Despite the incomplete fit to the tropical Brazil data, it would appear that diffusive gas loss, at the very least, provides a necessary and reasonable proxy to this seemingly ubiquitous aquifer fractionation process.

## Noble gas palaeotemperatures and The Last Glacial Maximum in the continental tropics

The noble gas palaeotemperature record has provided a key piece of evidence to support a 5°C drop in tropical continental regions at the last glacial maximum. The three tropical noble gas sample suites are from S.

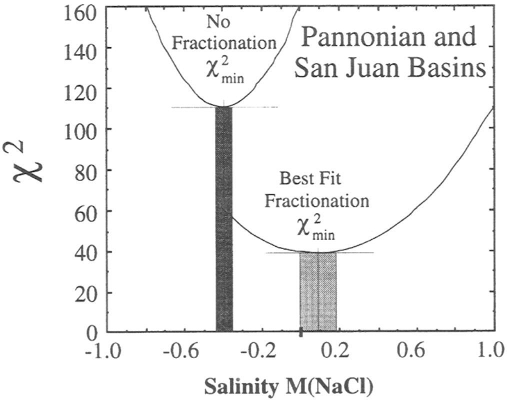

FIG. 1. The combined data set $\chi^2$ minimum defines the best fit recharge salinity. The inclusion of fractionation by diffusional gas loss is necessary to resolve the 'known' recharge salinity of meteoric water. Shaded areas = $\pm 1\sigma$ uncertainty.

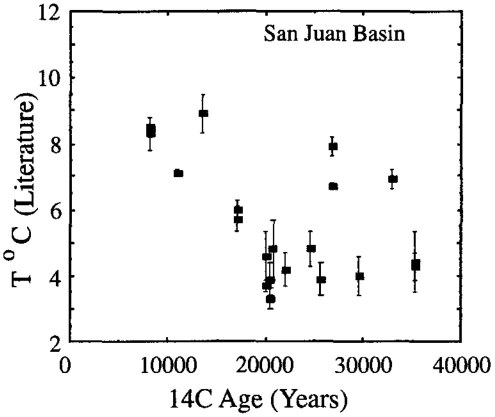

FIG. 2. Literature palaeotemperature used to support a 5°C temperature drop in the continental tropics at the LGM.

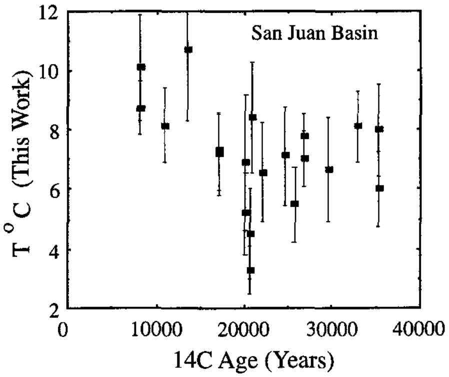

FIG. 3. Same data as Fig. 2, fitted for temperature, excess air and diffusive gas loss. Data now only accommodates a 1.9–2.5°C drop at the LGM.

Texas, the San Juan basin, New Mexico, and tropical Brazil (Stute *et al.*, 1992, 1995a,b). Of these data, it is impossible to assess the S. Texas data, because of uncertainty in the Ar abundance data quality. In the case of the tropical Brazil data, considering diffusive fractionation of the noble gases at recharge considerably improves the goodness of the fit of the data to the conceptual model. Nevertheless, by any statistical test the scatter in the tropical Brazil noble gas concentration data still requires significant unconstrained processes to be controlling the noble gas abundances in these samples. It is impossible to assess the effect such a 'process' would have on the derived palaeotemperature.

This leaves the San Juan sample suite (Fig. 2). When fitting for palaeotemperature, excess air and diffusive gas loss: 1) the sample suite shows optimal recharge salinity within error of meteoric water; 2) there is a significant improvement in fit for all data fit to the conceptual model; and 3) samples previously considered outliers now agree with samples of the same age. However, the San Juan data set now only supports a 1.9–2.5°C drop in tropical continental temperature at the LGM (Fig. 3).

Although this result is consistent with the foraminiferal assemblage, planktonic foraminifera $\delta^{18}$O and alkenone U-37(K′) techniques from low latitude deep sea cores which suggest that the tropical SST decreased by <2°C in the LGM (CLIMAP, 1981; Broeker, 1986; Sikes and Kegwin, 1994), this is quite different to the continental 5°C drop supported by snowline and vegetation changes (Rind and Peteet, 1985; Rind, 1990; Bush and Colinvaux, 1990; Colinvaux *et al.*, 1996), the 5°C drop in SST recorded by tropical coral Sr/Ca (Guilderson *et al.*, 1994; Beck *et al.*, 1997) and the Andean ice core $\delta^{18}$O record, which supports up to an 11°C drop at the LGM (Thompson *et al.*, 1995).

We offer no explanation for these differences but point out that the huge advantage of the noble gas palaeotemperature method is that unlike other palaeotemperature proxies it: 1) requires no empirical cross calibration with modern analogues; 2) does not require assumptions about the source isotopic composition (the non-radiogenic atmosphere noble gas inventory has been stable for billions of years); 3) is derived from fundamental physical properties; and 4) now provides a statistical test as to the validity of the physical processes proposed to account for the noble gas abundance pattern. The ability to estimate the precision of all fitted parameters for given noble gas abundance errors, as well as the ability to internally check the robustness of the conceptual model used to fit these parameters to the data is not available to any other palaeotemperature tool.

## References

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