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Low-^{18}O terranes tracking Mesozoic polar climates in the South Pacific

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Abstract—Substantially negative $\delta^{18}O$ values of altered rocks are an unfailing guide to ^{18}O-depleted meteoric water of low mean annual temperature, and therefore of cold climates at times of hydrothermal alteration. However, because water-rock interaction is often incomplete even where it has occurred, the lack of depleted values is poor evidence for lack of cold climate. A now established average surface rock composition of −6.6‰ $\delta^{18}O$, with a lower limit of −16‰, for an igneous and metamorphic terrane of some 6,000 km^2 in West Antarctica indicates Cretaceous meteoric water of less, or much less, than −20‰. This new anomaly and similar anomalies in New Zealand date from before rifting along the Antarctic-Pacific Rise and are tracking terranes originating from the Mesozoic south polar archipelago. In this area subaerial, or subglacial, hydrothermal isotope exchange has been particularly effective, and/or meteoric waters were isotopically unusually depleted. The discovery, mapping, and dating of further isotopically depleted zones in the geologic record will improve constraints for Paleozoic and Mesozoic greenhouse climates. *Copyright © 1997 Elsevier Science Ltd*

1. INTRODUCTION

The isotopes of oxygen and hydrogen offer quantitative evidence of fluid-rock interaction, and the past decades have improved and consolidated our understanding of magmatic and metamorphic hydrothermal systems (Criss and Taylor, 1986; Bickle and Mackenzie, 1987; Lassey and Blattner, 1988; Barnett and Bowman, 1995; Barnett et al., 1996). The effect of meteoric water on the $\delta^{18}O$ of rock, either directly by hydrothermal alteration or, more rarely, by magma assimilation of previously altered material, provides information on the active hydrothermal fluids. Where fluid throughput was high and meteoric isotope fronts are well advanced, the isotope shifts provide a window on past climates: given typical hydrothermal conditions, altered rock in polar or high altitude regions will approach δ-values far more negative than their low latitude and normal altitude counterparts. Similar reasoning applies to freshwater sediments, and continental scale isotopic gradients due to paleoclimate were first reported by Taylor (1974). How well this approach works for the recording of paleoclimate generally will depend on the frequency of high-throughput geothermal systems and freshwater sediments in the geologic record. Meanwhile, where they are found, low $\delta^{18}O$ or δD values of rock can set firm climatic limits (Bird and Chivas, 1988; Gregory et al., 1989; Blattner and Williams, 1991; Nevle et al., 1994). Here we report and discuss some of the most ^{18}O-depleted rocks known.

2. ANALYTICAL PROCEDURES

Oxygen and hydrogen isotope analyses were performed using a modified procedure after Clayton and Mayeda (1963) and a modified zinc reduction method (Woldemichael, 1993). Our reference scale is fixed to the recommended value 9.60‰ $\delta^{18}O$ (SMOW) of NBS28 and to a value of −63‰ δD (SMOW) for NBS30 (Gonfiantini, 1984). The mass spectrometer scale is normalised by NBS18 and SLAP. Standard deviations are about 0.3‰ for oxygen and 2‰ for hydrogen. For detailed comparison with other published data the reference values of the respective papers should be taken into account.

3. MEDIAN TECTONIC ZONE AND LOW-^{18}O TERRANES IN THE SOUTH PACIFIC

The Median Tectonic Zone (MTZ, earlier "Median Tectonic Line" and "H. Fyfe's Line", cf. Bradshaw, 1993; Kimbrough et al., 1993; Fleming, 1970) is essentially the New Zealand segment of the Pangea/Panthalassa, or later the Gondwana/Pacific, margin. We see it as a loosely defined collage of terranes, often volcanigenic, and generally related to subduction and rifting with associated transcurrent faulting along Gondwana coastlines. The eastern limit of the MTZ is the largely faulted boundary of the Permian Brook Street Terrane. In the west, the limits of Gondwana basement, and therefore the western margin of the MTZ, are less clear. A tectonic continuation of MTZ units of New Zealand into Marie Byrd Land and Thurston Island in the West Antarctic has been postulated for some years (Grindley and Davey, 1982; Adams, 1987; Grunow et al., 1991; Weaver et al., 1994; Kimbrough et al., 1994). Figure 1 shows a projection of the mid-Cretaceous West Antarctic archipelago.

3.1. Low-^{18}O Terranes of Southern New Zealand

A number of negative oxygen isotopic anomalies have been established in the South Island of New Zealand and are reported in detail by Blattner and Williams (1991) and Blattner (1996). From north to south they are as follows. Northwest of the Alpine Fault, the Drumduan Terrane was conceptually separated from the Permian Brook Street Terrane by Johnston et al. (1987) when, based on plant macrofossils, it was recognised as subaerial and of probable Jurassic age. Some of the plants actually occur in ^{18}O-depleted sediments, of 0 to 1‰ $\delta^{18}O$, whereas much lower δ-values of −4 to −9‰ are found in a larger and tectonically somewhat

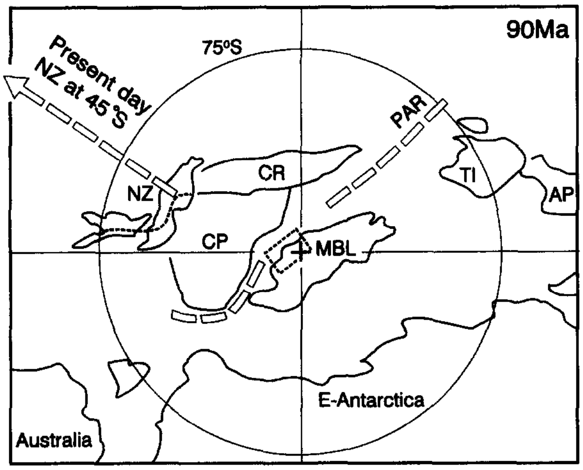

Fig. 1. Reconstruction of south polar archipelago at 90 Ma from Grunow et al. (1991); New Zealand after Grindley and Davey (1982) and Korsch and Wellman (1988). An 'overlay' of open symbols shows the subsequent drift of New Zealand (NZ) northward, away from the Pacific Antarctic rift (PAR). Median Tectonic Zone dashed. Rectangle is inset of Fig. 2. Remaining key: CR = Chatham Rise, CP = Campbell Plateau, MBL = Marie Byrd Land, TI = Thurston Island, AP = Antarctic Peninsula.

separate northern part of the Drumduan terrane. It is possible therefore, that the more negative 'northern Drumduan' values show an original pre-Jurassic anomaly, which has been eroded and inherited in a dispersed form by the plant-bearing metasediments. The lawsonite grade metamorphism (Johnston et al., 1987) could make it difficult to single out detrital minerals as carriers of the imprint.

Southeast of the Alpine Fault the meta-andesitic to -dacitic Largs Terrane displays an oxygen isotope anomaly to −12.3‰. The depleted pre-regional-metamorphic imprint resides mainly in the volcanic terrane, which has suffered intrusion and wholesale assimilation by the Mackay plutonic sequence. Only a 'halo' of less depleted oxygen extends into the plutonics, whose minerals including quartz are close to isotopic equilibrium (Blattner and Williams, 1991). The hydrothermal activity causing the isotopic imprint is therefore thought to date from before 224 Ma, when the Mistake Diorite and other Mackay Intrusives were emplaced (Bishop et al., 1990; Blattner and Graham, 1993; Kimbrough et al., 1994). Isotopic reconnaissance in the southernmost part of New Zealand including Stewart Island, shows values down to −7‰ $\delta^{18}O$ for the Paterson Group. This unit is largely of volcanigenic origin and has long been considered to be of Permian age. However, one zircon U/Pb date of Kimbrough et al. (1994) shows 146 Ma (Upper Jurassic). A well crystallised biotite gneiss of the Loch Burn Formation near Lake Monowai, shows −8‰.

3.2. Oxygen Isotopes of Marie Byrd Land

Based on plate tectonic analysis it was likely that the oxygen isotope anomalies of New Zealand would have counterparts in Marie Byrd Land, now more than 4000 km and 30° of latitude distant, provided they dated from before the spreading activity of the Pacific-Antarctic ridge. Present samples cover the heavily glaciated area of the Ruppert Coast and Hobbs Coast shown in Fig. 2 and are mostly from field collections of the second author. Our first analyses registered below −6‰ and it is apparent that in the zone of best coverage, near 140°W in Fig. 2, only four out of 24 in situ rocks have slightly positive $\delta^{18}O$ values, while 9 fall below −10‰ (Table 1A–D). The average δ-value for this 6,000 km^2 area is −6.6‰ (SE ±2‰). Two granites west of 150° (Edward VII Peninsula) were also examined, only one of which gave a normal result.

3.2.1. Geology

The field geological background of the Ruppert and Hobbs Coasts is as follows. Glacial erratics contain cleaved carbonaceous siltstone with Late Devonian plant fragments (Grindley and Mildenhall, 1981). Similar sedimentary rocks elsewhere in the area (Wilkins Nunatak) underlie meta-andesites to -dacites of greenschist metamorphic facies, with up to two stages of mesoscopic folding, and contain occasional unidentifiable plant fragments. Also present are somewhat deformed Carboniferous and Permo-Triassic granitoid plutons (Mt. McCoy, Kinsey Ridge; Mukasa, 1995; see Table 1). Their field relations, with contact metamorphism and assimilation (Spörli and Craddock, 1981), indicate intrusion into the older volcanics. The entire sequence of "Ruppert Coast Metavolcanics" (RCM) and "Wilkins Formation" (WF), containing the older granitoid intrusions, is intruded further by Cretaceous granitoids, which in places are superseded again by rhyolites, dacites, and basic dikes. Typical metamorphic minerals of the metavolcanics are indicated in Table 1B. The Cretaceous plutons and later dikes here and elsewhere along the Byrd Coast yield isotopic ages between 125 and 95 Ma (Adams et al., 1995; Weaver et al., 1994; and Table 1). This leaves a possible Devonian to Carboniferous age for the pre-granitoid sequence, if it is conformable with the Devonian of the erratics, but volcanics of Permo-Triassic or any later pre-Lower Cretaceous age may also occur. The post-granitoid volcanics, still cut by mafic dikes, are provisionally correlated with those of Mt Petras, at 128°W longitude (Petras Volcanics, PV). Weaver et al. (1994) ascribe the broadly granodioritic rocks with ages 124–108 Ma to an Early Cretaceous Andean-type active margin, and A-type granites, syenites, and gabbros of ages 102–95 Ma to rifting along the Pacific-Antarctic Ridge.

3.2.2. Oxygen isotope anomaly

In view of the 'normal' composition of only the Devonian siltstone erratic and the isotopic depletion to −16‰ of the Ruppert Coast Metavolcanics and Wilkins Formation, which were last intruded by Cretaceous granitoid plutons, most of the Ruppert Coast oxygen isotope anomaly may be due to hydrothermal systems associated with the Cretaceous intrusions. Two or (including no. P.51649) three Cretaceous granitoids have $\delta^{18}O$ below 0‰, with a probably Cretaceous microgranite dike at −13.1‰. These are hardly values caused by the energetically very limited contamination of

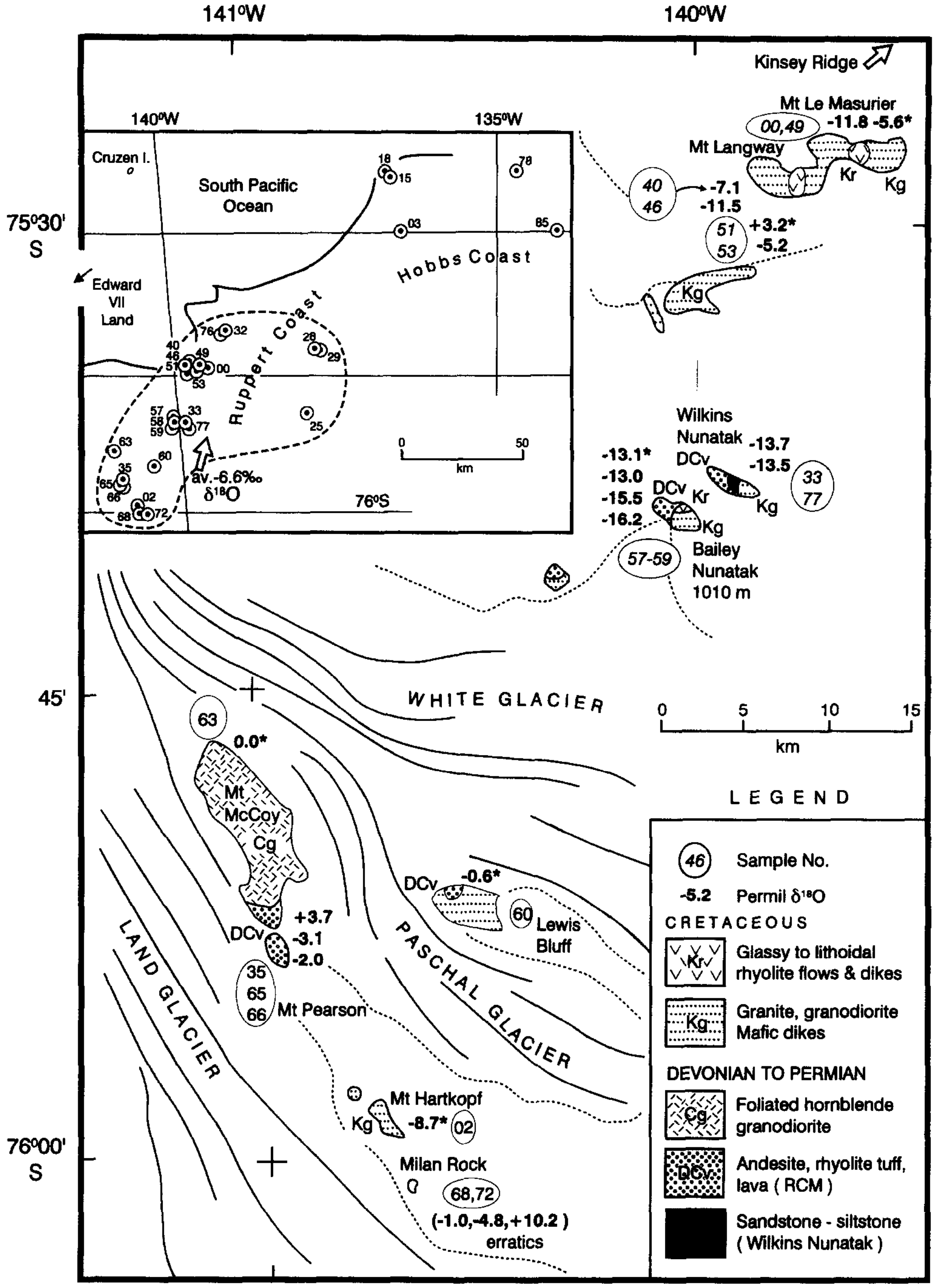

Fig. 2. Distribution of all samples (inset) and details of main oxygen isotope anomaly, Ruppert Coast. Numbers shown are the last two digits of the sample numbers of Table 1; asterisks mark granitoids. Inset also shows 6,000 km^2 area with average $\delta^{18}O$ value of −6.6‰. Edward VII Peninsula is at about 155°W.

magma with earlier anomalous rocks. Contamination would also have preceded the final isotopic equilibration between quartz and feldspars of the granitoids, as is the case, e.g., in the Mackay Intrusives (Blattner and Williams, 1991), whereas no. P.51649 and the two Paleozoic granites show strong isotopic shifts of their feldspars and lesser shifts of the rock-forming quartz. This is in accord with the relative ease of isotope exchange of feldspar as against of quartz and is strong evidence for concurrent isotopic exchange of RCM and granites. Only the dated Cretaceous monzodiorite no. P.51702 (112 Ma) has strongly shifted quartz in approximate equilibrium with the feldspar, the quartz clearly being of the primary rock-forming variety, filling interstices between the hypidiomorphic plagioclase. Equilibrium in this assemblage could mean that the end point of an L-shaped hydrothermal exchange path has been approached (e.g., Criss and Taylor,

TABLE 1: Oxygen isotope compositions of rock samples from Marie Byrd Land

A: Ruppert Coast, Granitoids

No. P-	Locality name	Latitude/longitude	Sample Description	δ¹⁸O, ‰	Ma
51632	Kinsey Ridge	75°22'/139°10'	Med to coa alkali granite, grey rock-forming quartz, 30%	-5.4 +1.4 Q	253 ± 4[1]
51649	Mt LeMasurier	75°27'/139°38'	Med to coa quartz monzonite, pink, feldspars clouded and with sericite Rock-forming quartz, 15%	-5.6 +2.8 Q	(sim. Mt. Langway)
51651	Mt Langway	75°29'/139°48'	Coa syenite to quartz syenite	+3.2	80.3±2.8 (hbl)
51657	Bailey Nunatak	75°39'/140°02'	Microgranite dike, pink, intrudes -658 and -659 Sub-mm quartz prisms from amygdales	-13.1 +5.2 Q	(intrudes Cret. lavas)
51660	Lewis Bluff	75°52.5'/140°30'	Med to coa hbl granite	-0.6	128 [2]
51663	Mt McCoy	75°47'/141°03'	Med to coa foliated hbl granite to quartz monzonite Rock-forming quartz, 20% Total rock (calculated)	-3.9 F +8.5 Q 0.0	320 ± 3 [3]
51702	Mt Hartkopf	75°59'/140°45'	Med hbl quartz monzodiorite, sl.pink, intrudes RCM Rock forming quartz, 15%	-8.7 -6.3 Q	112 ± 3 (hbl)

B: Ruppert Coast Metavolcanics (RCM), Wilkins Formation (WF)
Petras volcanics (PV) and erratics; metamorphic minerals in brackets

No. P-	Locality name	Latitude/ longitude	Sample description	δ¹⁸O, ‰	Ma
51625A 51625B	Krigsvold Nunatak	75°37'/138°01	Andesite (epi, chl, sph) (RCM) 1m andesite dike	-4.7 -5.5	
51628 51629	Lambert Nunatak	75°55'/137°54	Dolerite dike (act, sph) Andes. F.porphyry (act, chl, sph) (RCM)	+0.5 +0.1	98 ± 1.97 (TR)
51633	Wilkins Nunatak	75°39'/139°55	Volcaniclastic ss (epi, sph)(WF)	-13.7 ± 0.15 (2)	
51635	Mt Pearson	75°54'/140°59	Hbl porphyry (act, epi, sph) (RCM)	+3.7	
51640 51646 51653	Mt Langway	75°29'/139°48	Rhyolite dike, flow banded, pink (sph) (PV) Feldspar porphyry (epi) (PV) Aplitic zone in trachyandesite (PV)	-7.1 -11.5 -5.2	
51658 51659A 51659B	Bailey Nunatak	75°39'/140°02	Banded rhyolite sills & dikes (epi, sph)(PV) Volcanic breccia, matrix (epi, sph)(RCM) Basaltic fragments in same	-13.0 -15.5 -16.2 ± 0.4 (2)	
51665 51666	Mt Pearson	75°54'/140°59	Dacitic tuff breccia (RCM) Volcanigenic sandstone with plant fragments (RCM)	-3.1 -2.0	
51668A 51668B 51672	Milan Rock erratics	76°01'/140°40	Andesite fragment (epi, sph)(RCM) Breccia matrix (RCM) Siltstone with Devonian plants	-1.0 -4.8 +10.2	295 ± 5 (TR)
51676	Kinsey Ridge	75°22'/139°10	Thin beds of pelitic schist (WF) in schistose lavas and agglomerates	-10.4	105 ± 1.8 (TR)
51677	Wilkins Nunatak	75°39'/139°55	Non-volcanigenic ss. (WF) hornfels (bio, mus, chl) carbonaceous matter	-13.5	
51700	Mt LeMasurier	75°27'/139°39	Rhyolite with feldspar phenocrysts (PV)	-11.8	

Table 1. (Continued)

C: Cape Burks and Hobbs Coast

No. P-	Locality name	Latitude/ longitude	Sample description	$\delta^{18}O$, ‰	Ma
51578	Bowyer Butte	74°45'/134°45'	Coa granodiorite, pink, feldspar v.fresh	+8.0	
51585	Mt Prince	74°58'/134°10'	Microdiorite dikes	+1.8	103.8 ± 2 (TR)
51703	Dee Nunatak	74°58'/136°31'	Coa quartz syenite	+5.6	
51715	Cape Burks	74°46'/136°50'	Anorthositic gabbro	+0.8	103.5 ± 3 (TR)
51718A	Cape Burks	74°46'/136°50'	Pegmatoid hornblende granite feldspar	+2.4 hbl -1.6 F	99.8 ± 2 (hbl)
51718B	Cape Burks	74°46'/136°50'	Aplite	-3.9	

D: Edward VII Peninsula

No.	Locality name	Latitude/longitude	Sample description	$\delta^{18}O$, ‰	Ma
R13181	Bowman Pk	77°28'/153°30'	Byrd Coast Granite, pink	+0.8 F	98 ± 2 (bio) [4]
R13266	Washington Ridge	78°08'/155°11'	Byrd Coast Granite, pink	+10.4 F	101 ± 2 (bio) [5]

Abbreviations:

TR	Total Rock	chl	Chlorite
Med	Medium Grained	epi	Epidote
Coa	Coarse Grained	mus	Muscovite
hbl	Hornblende	ser	Sericite
act	Actinolite	sph	Sphene
F	Feldspar	bio	Biotite

Notes:

[1] Zircon U-Pb (Mukasa 1995)
[2] Total rock Rb-Sr (Halpern and Wade 1979)
[3] Zircon U-Pb (Mukasa 1995)
[4] Also part of Rb-Sr TR isochron of 102 ± 4 Ma (Adams et al. 1995)
[5] Also part of Rb-Sr TR isochron of 95 ± 3 Ma (Adams et al. 1995)

All other dates by K-Ar

1983; Barnett et al., 1996). This rock has in fact the most strongly altered feldspars, especially at their margins and including about 20 vol%, whereas the quartz shows no unusual optical extinction or structure. (Nevertheless, no. P.51632 from a pluton dated as Late Paleozoic also shows a strong isotopic shift of quartz and has fairly fresh feldspar.) For now the role of the Paleozoic plutons and that of the Petras Volcanics, which are mapped as post-granitoid by Grindley and Oliver (1983) and have $\delta^{18}O$ to $-13‰$, is still uncertain and a detailed petrologic study of this part of the Antarctic is clearly required. Granitoid no. P.51702, rather than being merely altered, could also represent a low-^{18}O magma. Taylor (1986) links such magmas with geotectonic rift settings. In the present case, a youngest age limit near 112 Ma seems likely for hydrothermal isotope exchange in this sample, because of the combined hornblende K-Ar date and negative $\delta^{18}O$ value of quartz. The minute quartz prisms ($\delta^{18}O$ = +5.2‰) from amygdales in a micrograninte (P.51657) are clearly late-stage; they are potentially in equilibrium with water of $-10‰$ at 200°C, or of $-20‰$ at some 100°C.

3.3. Hydrogen Isotopes

Hydrogen and oxygen isotopes are about equally sensitive indicators of the latitude and/or altitude of meteoric waters.

However, hydrogen ratios are imprinted more readily on, and hydrogen isotope fronts move faster through rocks, than is the case for the more abundant oxygen; a reverse exchange of hydrogen in hydrothermal or regional metamorphic events also takes place relatively readily. As a result hydrogen and oxygen isotopes in rocks will not correlate as simply as they do in meteoric waters. Six total rock samples from Drumduan and Largs Terranes were analysed by Woldemichael (1993) for δD with results of between −110 and −142‰ for Drumduan, but −71 and −90‰ for Largs (nos. O.U.35225 and O.U.35269 in Blattner and Williams, 1991). Preliminary analysis of Ruppert Coast samples gives −161‰ for hornblende of P.51663, −151‰ for total rock P.51676, and −150 ± 5‰ (2 det) for hornblende of P.51702. These last values are similar to those of Brandriss et al. (1995) from the Eocene of Greenland.

4. COMPARISON WITH OTHER ^{18}O-DEPLETED ROCKS

In spite of the large increase of oxygen isotope analyses produced in the last decades, coverage is insignificant in view of the stratigraphic record as a whole. It also seems likely that active hydrothermal systems are over-represented in stable isotope data. So far, some of the lowest recorded $\delta^{18}O$ values of altered common rock types appear to be −10.5‰ for basalt at active Krafla, Iceland (Hattori and Muehlenbachs, 1982), a similar value near −10‰ for Triassic eclogite from the Qinglong hills in NE-China (Yui et al., 1995), and the low end of the Largs anomaly in New Zealand, with −12.3‰ (Blattner and Williams, 1991). Secondary calcite from the Yangbajain geothermal system, which is recharged by water from altitudes near 6000 m, has −10.1‰ (Blattner et al., 1989). Nevle et al. (1994) mention feldspars "between +5.1 and −10.9‰" from East Greenland Eocene intrusives. Aharon (1988) reports subglacial aragonite precipitates with −15.7‰ from East Antarctica, and glacial moraine cements reach −10‰ (Schmidt and Friedman, 1974). In the last two cases and because of the large isotopic fractionation at low temperatures, the coexisting waters of about −40‰ are probably the isotopically most depleted waters known by their imprint in solid minerals. Hydrothermally altered rock values above −9‰ $\delta^{18}O$ are more frequent and Criss and Taylor (1986) list 56 active and extinct meteoric-hydrothermal systems, of which five (in addition to Krafla) have lower limits below −7‰. Of these only Krafla shows an average value below −4‰ (namely −7.7‰). Figure 3 shows a summary, including the most negative data from the list of Criss and Taylor (1986), as a background for the present West Antarctic and New Zealand results.

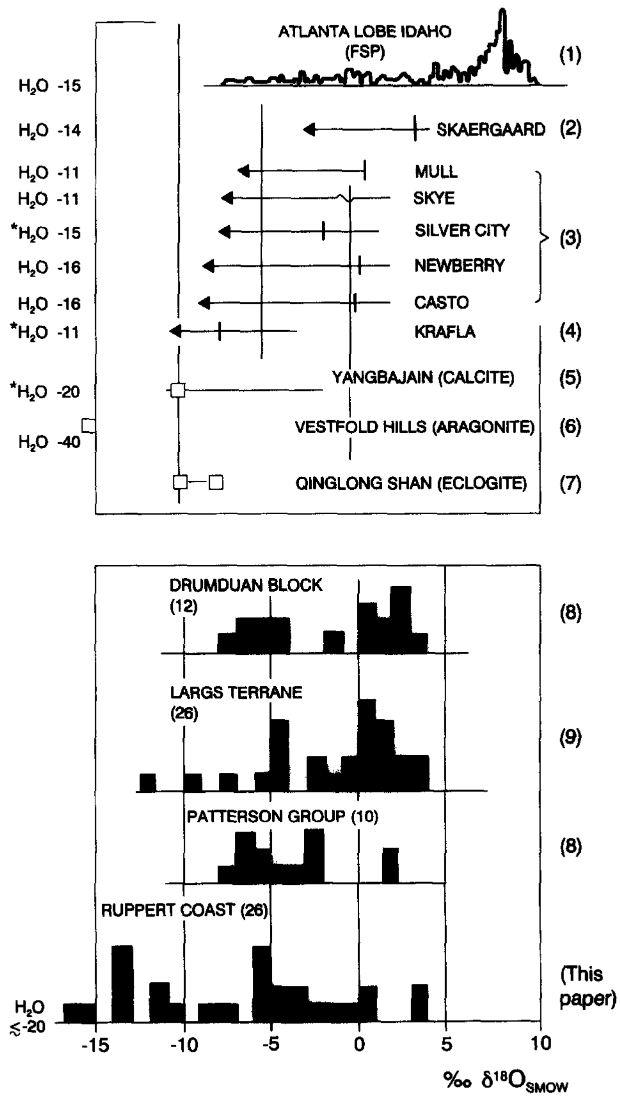

Fig. 3. Some of the lowest known $\delta^{18}O$ values of rocks and minerals. Where available, estimates or measurements of the $\delta^{18}O$ of water are given also (Asterisk marks active hydrothermal systems). Also see reference to Nevle et al. (1994) in text. For (2) to (4) arrowhead gives lowest value and a vertical line the mean. The New Zealand anomalies are in geographic order from N to S. Key: (1) Criss and Taylor (1983), (2) Taylor and Forester (1979), (3) Compilation of Criss and Taylor (1986), (4) Hattori and Muehlenbachs (1982), (5) Blattner et al. (1989), (6) Aharon (1988), (7) Yui et al. (1995), (8) Blattner (1996), (9) Blattner and Williams (1991).

5. TIGHTENING THE CLIMATE CONSTRAINT

In a warm and equable climate devoid of ice caps, H_2O representing the depleted end of the present-day isotopic 'meteoric water line' would physically recede to the upper atmosphere, with little chance, unless on the highest plateaux, of depleted hydrothermal imprints in rock. As a result, meteoric-hydrothermal oxygen isotope anomalies can provide constraints for extreme paleoclimatic and paleotectonic scenarios such as described, e.g., by Barron et al. (1989) and Worsley et al. (1994). The main limitation for hydrothermally altered rocks as isotopic indicators is that in any climate there are significant obstacles for solids to reach $\delta^{18}O$ values in equilibrium with the contemporary meteoric water. From a hydrological point of view a particular rock may never 'see' actual meteoric water, but only waters that have already been altered along a flow path. From a kinetic point of view, hydrothermal systems usually run at 200–350°C, so that limits on recrystallisation and isotope exchange are significant. In addition, uneven permeability or channelling lead to poorly predictable distributions of any particular δ-values of rock, including the sought-after most extreme ones. The resulting hydrological, climatic, and statistical sampling gap, which is a function of the internal structure of the given meteoric isotope fronts, permits $\delta^{18}O$ and δD values calculated from rock only to approach actual meteoric values from the positive side. The large spread of data for feldspar in part of the Idaho batholith, graphed at the top of Fig. 3, from Criss and Taylor (1983)($\delta^{18}O$ of water, −15‰) suggests a typical highly dispersed infiltration front. The Skaergaard system, although supplied by a similarly depleted water with −14‰, now shows even less negative rock values, perhaps because the most depleted part of the reservoir has been eroded away (Norton and Taylor, 1979). The ^{18}O-depleted rocks of the Ruppert Coast reach −16‰ $\delta^{18}O$, some 8‰ below the lower limit for the Idaho batholith and several other fossil geothermal systems recorded in Fig. 3 with assigned waters near −15‰, which already resembles water from present-day inland Iceland (cf. Hattori and Muehlenbachs, 1982). Therefore, by simple analogy, the Ruppert Coast Cretaceous meteoric waters would have −23‰ $\delta^{18}O$ (and from this, some −180‰ δD). In an extreme case, subglacial hydrothermal activity with a water supply of −40‰ $\delta^{18}O$ (δD c. −320‰) could cause isotopic shifts of silicate rock to well below −30‰ $\delta^{18}O$ and −300‰ δD. Because of the different parameters governing the infiltration and exchange of hydrogen and oxygen isotopes, full combined datasets will no doubt prove useful in the future, but only further sampling, informed by tectonics and petrology, can tighten the isotopic constraints in the West Antarctic Cretaceous or in other parts of the geologic record.

6. CONCLUSION

The discovery of the pronounced Ruppert Coast oxygen isotope anomaly at an original Cretaceous latitude of some 80°S (now 75°S) bears out the earlier conclusion that the Largs, Drumduan, and other oxygen isotopic imprints, now at 45°S latitude in New Zealand, were caused by a colder climate than the present one. The addition of this anomaly to those of the MTZ in a coherent regional pattern strongly encourages the search for further pieces of the paleoclimate puzzle. We note that the magnetically inferred rotational South Pole has remained in the SE Australian-New Zealand-W Antarctic archipelago throughout Mesozoic times, providing a basis for the comparison of climate variations against a relatively steady latitude. Bird and Chivas (1988) deduced $\delta^{18}O$ values for Australian Early Permian waters of less than −17‰ (possible glacier run-off) and Gregory et al. (1989) found an average near −20‰ (and calculated a surface temperature below 0°C) for Early Cretaceous water. If the Largs anomaly of New Zealand is of immediate pre-224 Ma Triassic age, it dates from close to the time of the 'coal gap' of Permian/Triassic stratigraphy, sometimes presumed to be a relatively warm period (Veevers et al., 1994; Faure et al., 1995).

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