



**HAL**  
open science

## Gravitational separation in polar firn. Response to H CRAIG.

D. Raynaud, J. Barnola, J. Chappellaz, R. Delmas, C. Lorius, J. Jouzel, J.  
Schwander

► **To cite this version:**

D. Raynaud, J. Barnola, J. Chappellaz, R. Delmas, C. Lorius, et al.. Gravitational separation in polar firn. Response to H CRAIG.. Science, 1993, 262 (5134), pp.764-764. 10.1126/science.262.5134.764 . hal-03340138

**HAL Id: hal-03340138**

**<https://hal.science/hal-03340138>**

Submitted on 29 Sep 2021

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

**Harmon Craig**  
Scripps Institution of Oceanography,  
University of California, San Diego,  
La Jolla, CA 92093

#### REFERENCES AND NOTES

1. D. Raynaud, J. Jouzel, J. M. Barnola, J. Chappellaz, R. J. Delmas, C. Lorius, *Science* **259**, 926 (1993); *ibid.* **260**, 1411 (1993).
2. J. Schwander, J.-M. Barnola, C. Andrie, M. Leuenberger, A. Ludin, D. Raynaud, B. Stauffer, *J. Geophys. Res.* **98**, 2831 (1993).
3. H. Craig, Y. Horibe, T. Sowers, *Science* **242**, 1675 (1988); carrier diffusion [H. Craig, *ibid.* **159**, 93 (1968)] is another process that may be responsible for fractionation effects.
4. T. Sowers, M. Bender, D. Raynaud, *J. Geophys. Res.* **94**, 5137 (1989).
5. Note however, that the elemental enrichment order deduced by Sowers *et al.* from their data [(4), p. 5147] is that air gases are lost in the order Ar, O<sub>2</sub>, N<sub>2</sub>, which is stated to be that predicted from molecular diameters, following (3). This is an error: their data actually show that the order of gas loss in their samples is O<sub>2</sub>, Ar, N<sub>2</sub>, as predicted and observed (3).
6. H. Craig, *Eos* **69**, 1211 (1988); \_\_\_\_\_, D. Burtner, R. C. Wiens, *ibid.* **70**, 1151 (1989).

7 May 1993; accepted 20 July 1993

**Response:** Craig discusses the O<sub>2</sub>/N<sub>2</sub> ratios shown by Schwander *et al.* (1), but it was not stated in that paper that these ratios illustrated gravitational fractionation. Furthermore, in our *Science* article (2), we discussed exclusively the ice record of greenhouse gases (especially CO<sub>2</sub> and CH<sub>4</sub>); our reference to Schwander *et al.* (1) concerned the CO<sub>2</sub> and CH<sub>4</sub> results of that paper.

Gases will be gravitationally fractionated only if the ratio of the diffusivity (*D*) to the convection velocity (*w*) is larger than

the firm thickness; indeed they must then be fractionated. This condition is satisfied, at least for the Greenland site of Summit (1), and so gases in the firm are in fact enriched in heavier elements and isotopes because of gravitation. This argument was first made by Craig *et al.* [note 14 in (3)], who pointed out that the assumption was first made that "gases . . . continuously readjust to the time-independent equilibrium state . . . is approximately true." The dominance of the diffusivity is also clearly indicated by the <sup>85</sup>Kr, CO<sub>2</sub>, and CH<sub>4</sub> data measured in the firm at Summit (1). These results could not be explained if the diffusive equilibrium were not closely fulfilled; effusion at Summit obviously plays a minor role, but additional effects on gas fractionation are not ruled out.

Craig predicts that firm air enrichments in <sup>18</sup>O will differ by up to 0.15 per mil depending on whether fractionation in the firm results from effusion or gravitational fractionation. Analytical precision allows one to look at such a difference. Craig *et al.* (3), for example, noted that the maximum δ<sup>15</sup>N and δ<sup>18</sup>O enrichments for the D57 ice core are predicted exactly from the firm depths and temperatures for gravitational equilibrium. We note that the δ<sup>18</sup>O values would need to be shifted by 0.1 per mil to be explained by effusion, when the experimental accuracy is 0.04 per mil.

On the basis of such observations, Craig *et al.* wrote (3, p. 1678)

Thus, 60 years after publication of the canonical theorem of Gibbs, a fluid system at the earth's surface—atmospheric gases in the firm layers of

polar ice caps—has provided experimental verification [italics ours] of this effect . . .

namely, gravitational fractionation.

Finally, Craig's <sup>84</sup>Kr/<sup>36</sup>Ar measurements appear to confirm the role of gravitational fractionation.

**D. Raynaud**  
**J. M. Barnola**  
**J. Chappellaz**  
**R. J. Delmas**  
**C. Lorius**

Laboratoire de Glaciologie et Géophysique de l'Environnement (LGGE),  
Centre National de la Recherche Scientifique,  
BP 96, 38402 Saint Martin d'Hères Cedex,  
France

**J. Jouzel**  
Laboratoire de Modélisation du Climat et de l'Environnement,  
Commissariat à l'Energie Atomique Saclay,  
91191 Gif sur Yvette Cedex, France, and  
LGGE, Centre National de la Recherche  
Scientifique

**J. Schwander**  
Institut Physikalisches, Universität Bern,  
Sidlerstrasse 5, 3012 Bern, Switzerland

#### REFERENCES AND NOTES

1. J. Schwander, J. M. Barnola, C. Andrieu, M. Leuenberger, A. Ludin, D. Raynaud, B. Stauffer, *J. Geophys. Res.* **98D**, 2831 (1993).
2. D. Raynaud, J. Jouzel, J. M. Barnola, J. Chappellaz, R. J. Delmas, C. Lorius, *Science* **259**, 926 (1993); *ibid.* **260**, 1411 (1993).
3. H. Craig, Y. Horibe, T. Sowers, *ibid.* **242**, 1675 (1988).
4. We thank M. Bender for useful discussions.

25 June 1993; accepted 20 July 1993

## **Response: Gravitational Separation in Polar Firn**

D. Raynaud, J. M. Banola, J. Chappellaz, R. J. Delmas, C. Lorius, J. Jouzel, and J. Schwander

*Science*, 262 (5134),

### **View the article online**

<https://www.science.org/doi/10.1126/science.262.5134.764>

### **Permissions**

<https://www.science.org/help/reprints-and-permissions>