

[4]

# Subducted and recycled lithosphere as the mantle source of ocean island basalts from southern Polynesia, central Pacific

C. DUPUY<sup>1</sup>, H.G. BARSCZUS<sup>1,2</sup>, J. DOSTAL<sup>3</sup>, P. VIDAL<sup>4</sup> and J.-M. LIOTARD<sup>1</sup>

<sup>1</sup>Centre Géologique et Géophysique, C.N.R.S. et Université des Sciences et Techniques du Languedoc, F-34060 Montpellier Cédex (France)

<sup>2</sup>Centre ORSTOM de Tahiti, Papeete (French Polynesia)

<sup>3</sup>Department of Geology, Saint Mary's University, Halifax, N.S. B3H 3C3 (Canada)

<sup>4</sup>UA 10 C.N.R.S. et Université, F-63018 Clermont-Ferrand Cédex (France)

(Received October 13, 1988; revised and accepted April 4, 1989)

## Abstract

Dupuy, C., Barszczus, H.G., Dostal, J., Vidal, P. and Liotard, J.-M., 1989. Subducted and recycled lithosphere as the mantle source of ocean island basalts from southern Polynesia, central Pacific. *Chem. Geol.*, 77: 1-18.

The Marquesas, Society and Austral-Cook Islands, three volcanic chains in the central Pacific Ocean (French Polynesia), are composed mainly of alkali basalts, basanites and tholeiites, which have geochemical characteristics typical of ocean island basalts. The lavas from the Marquesas and Society Islands display generally chondritic ratios of highly incompatible trace elements and have higher <sup>87</sup>Sr/<sup>86</sup>Sr than the basalts from the Austral-Cook Islands which have many trace-element ratios similar to those of mid-ocean ridge basalts. This grouping probably reflects differences in the composition of an ancient subducted and recycled lithosphere incorporated into the mantle source of the Polynesian basalts. Compared to Marquesas and Society Islands basalts, the mantle source of the Austral-Cook Islands basalts contains refractory oceanic lithosphere from which a larger amount of basaltic melt was extracted during subduction.

## 1. Introduction

Ocean island basalts (OIB) are usually considered to be generated by melting of an upper-mantle source enriched in incompatible elements by CO<sub>2</sub>-rich fluids or undersaturated melts derived from the low-velocity zone (LVZ) (e.g., Green, 1971; McCulloch et al., 1983; Hart, 1988; Nelson et al., 1988). Alternatively, it has been suggested (e.g., Hofmann and White, 1980, 1982) that subduction of the oceanic lithosphere can produce compositionally distinct regions within the convecting mantle involved in

the generation of OIB. Ringwood (1982, 1986) has argued that the subducted oceanic lithosphere made out of oceanic crust and refractory harzburgite buckled and thickened at the base of the upper mantle and subsequently formed large megaliths. Such peridotite diapirs which are enriched in incompatible trace elements (ITE) by melts derived from the subducted oceanic crust may become the source of OIB. Although some recent findings suggest a more complex scenario (Kato et al., 1988), the latter model has been invoked for basalts of the Austral Islands (French Polynesia); their mantle

source was probably formed by mixing of the depleted upper mantle with subducted oceanic crust from which melts with island-arc basalt (IAB) composition were previously extracted (Dupuy et al., 1988).

In this paper we present data which indicate that basalts from other Polynesian island chains might also be generated from an ancient subducted and recycled lithosphere. The new analyses confirm the existence of geochemical heterogeneities of the mantle source of basaltic rocks from the different Polynesian island chains, which can be explained by the mixing of the oceanic crust and residual peridotite.

## 2. Geological notes

Southern Polynesia in the central Pacific Ocean is composed of the Marquesas, Tuamotu, Pitcairn-Gambier, Society and Austral-Cook archipelagos (Fig. 1). These roughly NW-SE-trending island chains are cross-cut by two major fossil fracture zones: the Marquesas and Austral fracture zones. The islands are predominantly made up of basalt (except the Tuamotu Islands which are coral atolls) with subordinate amounts of differentiated products such as phonolites and trachytes. The ages of these volcanics are variable according to the island chain. The oldest recorded ages are 19.5 Ma in the Austral-Cook (AC) Islands (Turner and Jarrard, 1982), 4.5 Ma in the Society (SO) Islands (Duncan and McDougall, 1976), 6 Ma in the Pitcairn-Gambier Islands (Bellon, 1974) and ~6 Ma in the Marquesas (MA) Islands (J.H. Cantagrel, pers. commun., 1988). In all the island chains the ages decrease from NW to SE and two of them have still active submarine volcanism: Mehetia-Teahitia seamount region in the SO Islands (e.g., Talandier and Okal, 1984) and Macdonald Seamount in the AC Islands (Norris and Johnson, 1969). In most cases a typical correlation between island age and distance to hot spot is apparent (McDougall and Duncan, 1980), but two noticeable exceptions have been observed in the AC Is-

lands: at Rurutu both old (12 Ma) and young (1 Ma) basalts have been reported (Dalrymple et al., 1975; Duncan and McDougall, 1976) as well as at Aitutaki (~1 and ~8 Ma; Turner and Jarrard, 1982).

The age of sea floor inferred from magnetic lineations 6-34 present in this region (CPCEMR, 1981) ranges from 20 Ma (east of Pitcairn) to more than 80 Ma (west of the Society Islands). Various geophysical data suggest that the mantle which underlies southern Polynesia has anomalously high temperatures (Nishimura and Forsyth, 1985; Calmant and Cazenave, 1986, 1987; Haxby and Weissel, 1986) and that the source for the excess heat is located in the asthenosphere (McNutt and Fischer, 1987).

## 3. Samples and analytical methods

From the set of MA and AC samples which were previously analyzed for major and some trace elements (Liotard et al., 1986; Dupuy et al., 1988), 32 representative basalts were selected for the determination of U and Ta. In addition, 114 other basaltic samples from the AC, MA and SO archipelagos, particularly from the islands for which only very few data are available, were analyzed for major and 19 trace elements. The samples were selected according to their degree of freshness after inspection of thin sections. The powders to be analyzed were prepared by extracting centimeter-size fragments from coarsely crushed material. The fragments were washed in cold distilled water in an ultrasonic bath. Up to 60 g of such rock fragments were ground to powder in an agate mill.

Major elements and Li were determined by atomic absorption spectrometry; Rb, Sr, Ba, Zr, Y and Nb by X-ray fluorescence and rare-earth elements (REE), Hf, Th, Ta and U by instrumental neutron activation. The precision and accuracy of the trace-element analyses have been discussed elsewhere (Dostal et al., 1986). For most elements the precision is better than  $\pm 5\%$ . New analyses are reported in Table I.

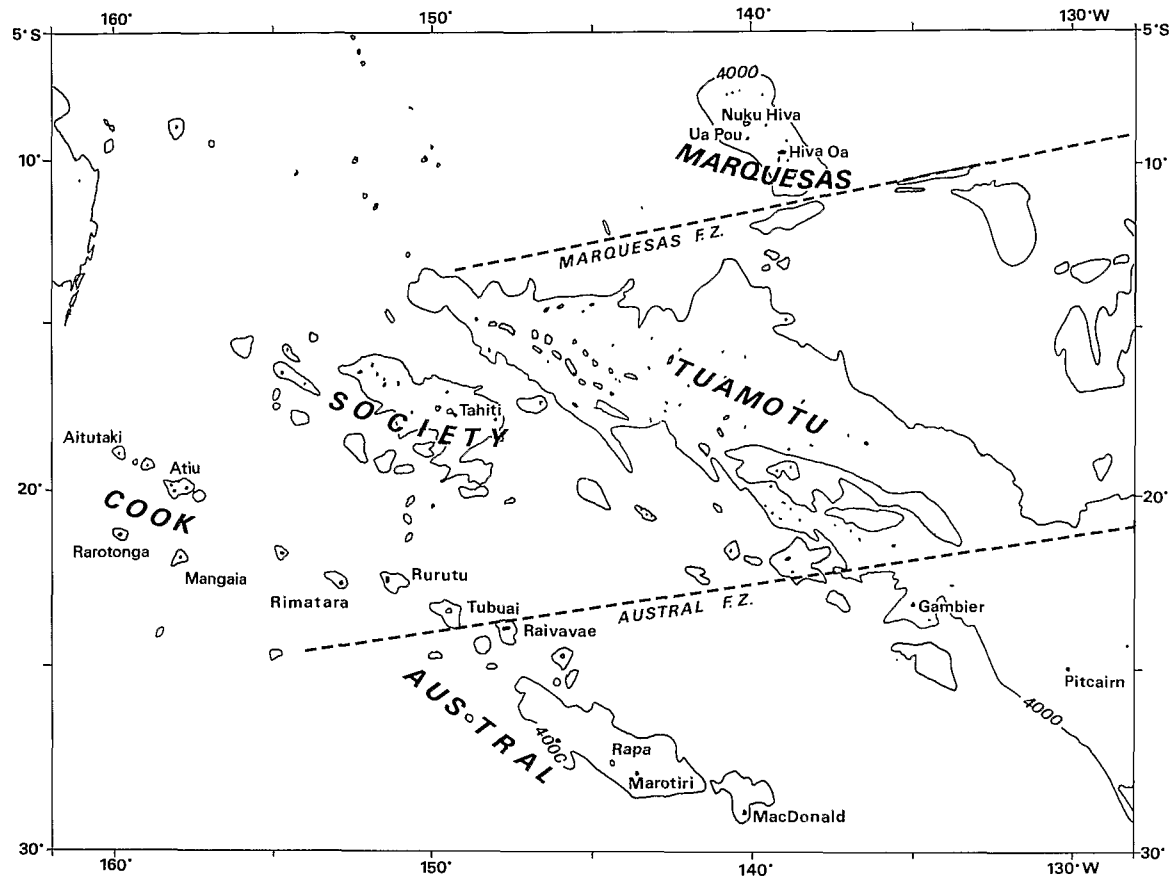


Fig. 1. Location of the various Polynesian archipelagos in the south central Pacific Ocean.

#### 4. Geochemistry

The geochemical characteristics of the basalts from the Marquesas, Austral-Cook and Society volcanic island chains have been described by Dostal et al. (1982), Liotard et al. (1986), Palacz and Saunders (1986), Dupuy et al. (1987, 1988), and Vidal et al. (1987) and are briefly reviewed here. On the other hand, as only very few data for the Cook Islands have been previously reported (Palacz and Saunders, 1986), a more detailed description for the Cook Islands basalts is given. The three island groups will be referred to as AC (Austral-Cook), MA (Marquesas) and SO (Society), respectively.

In each island chain, the normative composition of the basalts usually indicates the presence of four magmatic types: quartz tholeiites,

olivine tholeiites, alkali basalts and basanites. However, the proportion of the basaltic types are variable: in the SO and MA Islands the amounts of olivine tholeiites and alkali basalts appear to be equal, whereas alkali basalts and basanites are more abundant in the AC. All basalts have trace-element features characteristic of OIB: high contents of incompatible trace elements (ITE) and REE patterns marked by an enrichment in light REE (LREE) and fractionation of heavy REE (HREE). The ITE concentrations vary within a large range and exhibit an increase both with differentiation and degree of undersaturation (e.g., Liotard et al., 1986). The chondrite-normalized ITE patterns and the corresponding element ratios are variable. For example, the Ba/Nb ratio varies between 3 and 13 and distinguishes MA basalts

TABLE I

Major- and trace elements contents of samples from southern Polynesia

|                                | 6565<br>EAO-11<br>TH | 6602<br>UAP-24<br>TH | 8148<br>UAP-227<br>TH | 7467<br>UP-73F<br>BSN | 7468<br>UP-74H<br>AB | 6453<br>FTK-13<br>AB | 6198<br>MAP<br>BSN | 4639<br>ME-7<br>BSN | 4640<br>ME-17<br>BSN | 4635<br>THT-1A<br>AB | 4636<br>THT-2S<br>BSN | 4634<br>RA-24H<br>BSN |
|--------------------------------|----------------------|----------------------|-----------------------|-----------------------|----------------------|----------------------|--------------------|---------------------|----------------------|----------------------|-----------------------|-----------------------|
| SiO <sub>2</sub> (wt.%)        | 47.71                | 46.1                 | 46.96                 | 42.8                  | 43.81                | 46.16                | 41.54              | 42.5                | 43.87                | 44.46                | 46.42                 | 42.51                 |
| Al <sub>2</sub> O <sub>3</sub> | 14.17                | 13.35                | 13.44                 | 11.77                 | 14.74                | 13.42                | 13.76              | 9.8                 | 11.5                 | 11.77                | 13.2                  | 11.75                 |
| Fe <sub>2</sub> O <sub>3</sub> | 13.35                | 13.04                | 13.5                  | 15.12                 | 12.52                | 13.06                | 11.8               | 14.3                | 14.4                 | 13.37                | 12.18                 | 14.52                 |
| MnO                            | 0.21                 | 0.14                 | 0.18                  | 0.16                  | 0.18                 | 0.18                 | 0.15               | 0.17                | 0.17                 | 0.17                 | 0.17                  | 0.17                  |
| MgO                            | 5.63                 | 5.53                 | 6.42                  | 8.39                  | 4.88                 | 7.75                 | 6.64               | 15.72               | 11.51                | 9.73                 | 10.6                  | 12.37                 |
| CaO                            | 10.18                | 11.18                | 11.3                  | 12.74                 | 8.67                 | 10.75                | 13.5               | 10.37               | 10.14                | 13.36                | 9.76                  | 10.24                 |
| Na <sub>2</sub> O              | 2.79                 | 2.85                 | 2.65                  | 2.38                  | 2.33                 | 2.85                 | 2.58               | 2.81                | 2.94                 | 1.56                 | 3.19                  | 2.41                  |
| K <sub>2</sub> O               | 0.93                 | 0.74                 | 0.37                  | 1.07                  | 2.45                 | 1.24                 | 0.89               | 0.68                | 1.46                 | 0.77                 | 1.23                  | 1.54                  |
| TiO <sub>2</sub>               | 3.39                 | 4.29                 | 3.81                  | 3.4                   | 3.72                 | 3.57                 | 3.5                | 3.28                | 3.7                  | 3.55                 | 2.54                  | 3.87                  |
| P <sub>2</sub> O <sub>5</sub>  | 0.49                 | 0.57                 | 0.46                  | 0.34                  | 1.16                 | 0.7                  | 0.67               | 0.51                | 0.66                 | 0.48                 | 0.59                  | 0.62                  |
| LOI                            | <u>0.39</u>          | <u>1.36</u>          | <u>0.56</u>           | <u>1.59</u>           | <u>4.85</u>          | <u>0.39</u>          | <u>5.14</u>        | <u>0.8</u>          | <u>0.71</u>          | <u>2.3</u>           | <u>1.02</u>           | <u>1.2</u>            |
| Total                          | 99.24                | 99.15                | 99.65                 | 99.76                 | 99.31                | 100.07               | 100.17             | 100.94              | 101.06               | 101.52               | 100.9                 | 101.2                 |
| [Mg]                           | 0.49                 | 0.49                 | 0.52                  | 0.55                  | 0.46                 | 0.57                 | 0.56               | 0.71                | 0.64                 | 0.62                 | 0.66                  | 0.66                  |
| Li (ppm)                       | 6                    | 5                    | 4                     | 6                     | 10                   | 6                    | 14                 | 5                   | 6                    | 6                    | 7                     | 6                     |
| Rb                             | 16                   | 11                   | 5                     | 58                    | 115                  | 26                   | 18                 | 11                  | 38                   | 11                   | 31                    | 38                    |
| Sr                             | 491                  | 610                  | 523                   | 539                   | 1,360                | 794                  | 725                | 640                 | 750                  | 680                  | 820                   | 743                   |
| Ba                             | 315                  | 164                  | 109                   | n.d.                  | n.d.                 | 250                  | 311                | 335                 | 435                  | 370                  | 425                   | 410                   |
| Y                              | n.d.                 | 37                   | 37                    | n.d.                  | n.d.                 | 33                   | 33                 | 24                  | 30                   | 28                   | 25                    | 27                    |
| Zr                             | n.d.                 | 419                  | 316                   | n.d.                  | n.d.                 | 247                  | 289                | 250                 | 305                  | 288                  | 214                   | 298                   |
| Nb                             | 26.6                 | 34                   | 34                    | n.d.                  | n.d.                 | 29                   | 36.9               | 36                  | 43                   | 36                   | 57                    | 43                    |
| La                             | 26.41                | 28.36                | 24.2                  | 34.3                  | 80.5                 | 24.94                | 32.9               | 32.1                | 42.1                 | 33.4                 | 33.6                  | 39.7                  |
| Ce                             | 64.7                 | 77.58                | 61.3                  | 76.7                  | 188.1                | 63.49                | 88                 | 73.6                | 97.3                 | 79.2                 | 68.2                  | 88.1                  |
| Nd                             | 34.2                 | 57.91                | 40.8                  | 29.9                  | 71.6                 | 39.4                 | 45                 | 39.4                | 48.4                 | 42.3                 | 30.7                  | 45.4                  |
| Sm                             | 8.96                 | 13.05                | 10.02                 | 6.58                  | 12.91                | 9.02                 | 10.55              | 8.3                 | 10.6                 | 9.2                  | 6.8                   | 10.1                  |
| Eu                             | 2.88                 | 4.12                 | 3.26                  | 2.08                  | 3.78                 | 3.02                 | 3.32               | 2.72                | 3.46                 | 2.95                 | 2.26                  | 3.03                  |
| Tb                             | 1.34                 | 1.47                 | 1.52                  | 0.67                  | 1.02                 | 1.11                 | 1.31               | 1                   | 1.24                 | 1.2                  | 0.89                  | 1.01                  |
| Yb                             | 2.65                 | 2.37                 | 2.45                  | 1.59                  | 2.38                 | 2.2                  | 2.3                | 1.43                | 1.63                 | 2.01                 | 1.77                  | 1.46                  |
| Lu                             | 0.39                 | 0.33                 | 0.38                  | 0.26                  | 0.34                 | 0.31                 | 0.34               | 0.18                | 0.22                 | 0.26                 | 0.25                  | 0.25                  |
| Hf                             | 6.4                  | 9.3                  | 7                     | 4.9                   | 9.1                  | 5.61                 | 6.6                | 5.6                 | 6.9                  | 6.7                  | 4.6                   | 6.8                   |
| Ta                             | 1.75                 | 2.3                  | 2.3                   | 2.6                   | 6.2                  | 2.15                 | 2.35               | 2.19                | 2.58                 | 2.4                  | 2.18                  | 2.56                  |
| Th                             | 3.2                  | 2.47                 | 2.2                   | 5.8                   | 12.4                 | 2.1                  | 3.3                | 4.2                 | 6.7                  | 3.6                  | 4.6                   | 4.9                   |
| U                              | 0.6                  | 0.7                  | 0.47                  | 0.95                  | 2.2                  | 0.6                  | 6.16               | 0.87                | 1.7                  | 0.6                  | 1.09                  | 1.33                  |

TABLE I (continued)

|                                | 4641<br>TA-25B<br>TH | 4642<br>TA-25F<br>AB | 4631<br>BB-20S<br>TH | 4629<br>BB-20F<br>TH | 4628<br>BB-20E<br>TH | 6966<br>MCD-44<br>TH | 6972<br>MCD-72<br>BSN | 6988<br>MRT-01<br>BSN | 3656<br>RA-27<br>AB | 7258<br>RPA-02<br>AB | 7268<br>RVV-02<br>AB | 7275<br>RVV-123<br>TH |
|--------------------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|-----------------------|-----------------------|---------------------|----------------------|----------------------|-----------------------|
| SiO <sub>2</sub> (wt.%)        | 47                   | 46.62                | 46.03                | 47                   | 49.16                | 47.47                | 42.77                 | 43.75                 | 45                  | 44                   | 46.8                 | 47.57                 |
| Al <sub>2</sub> O <sub>3</sub> | 12.12                | 12.71                | 10.64                | 13.94                | 14                   | 15                   | 11.28                 | 18.17                 | 15.06               | 11.69                | 14                   | 11.63                 |
| Fe <sub>2</sub> O <sub>3</sub> | 12.3                 | 12.34                | 13.08                | 13.06                | 12.16                | 12.58                | 13.78                 | 11.43                 | 12.45               | 13.55                | 12.33                | 12.86                 |
| MnO                            | 0.15                 | 0.15                 | 0.17                 | 0.17                 | 0.14                 | 0.15                 | 0.17                  | 0.16                  | 0.16                | 0.16                 | 0.15                 | 0.15                  |
| MgO                            | 10.48                | 9.32                 | 16                   | 6.63                 | 5.53                 | 5                    | 12.08                 | 3.5                   | 5.96                | 13.1                 | 7.67                 | 13.15                 |
| CaO                            | 9.15                 | 9.55                 | 8.64                 | 11.21                | 10.21                | 10.2                 | 11.15                 | 9.91                  | 10.7                | 9.95                 | 10.6                 | 8.9                   |
| Na <sub>2</sub> O              | 2.21                 | 3.25                 | 2                    | 2.48                 | 2.92                 | 3.5                  | 2.85                  | 4.88                  | 2.92                | 2.46                 | 2.94                 | 2.35                  |
| K <sub>2</sub> O               | 1.81                 | 0.72                 | 0.83                 | 1.33                 | 1.55                 | 0.4                  | 0.97                  | 1.98                  | 1.29                | 1.07                 | 0.87                 | 0.46                  |
| TiO <sub>2</sub>               | 3.2                  | 3.11                 | 2.04                 | 3.5                  | 2.9                  | 3.1                  | 3.46                  | 2.97                  | 3.7                 | 3.58                 | 2.8                  | 2.19                  |
| P <sub>2</sub> O <sub>5</sub>  | 0.52                 | 0.6                  | 0.29                 | 0.52                 | 0.47                 | 0.4                  | 0.54                  | 0.9                   | 0.77                | 0.59                 | 0.48                 | 0.31                  |
| LOI                            | 1.69                 | 2.19                 | 1.37                 | 1.2                  | 1.98                 | 1.59                 | 0.51                  | 1.66                  | 2.24                | 0.5                  | 0.99                 | 0.34                  |
| Total                          | 100.63               | 100.56               | 101.09               | 101.04               | 101.02               | 99.39                | 99.56                 | 99.31                 | 100.25              | 100.65               | 99.63                | 99.91                 |
| [Mg]                           | ~ 0.66               | 0.63                 | 0.73                 | 0.53                 | 0.50                 | 0.47                 | 0.66                  | 0.41                  | 0.51                | 0.69                 | 0.58                 | 0.70                  |
| Li (ppm)                       | 6                    | 6                    | 5                    | 6                    | 5                    | 5                    | 6                     | 8                     | 8                   | 8                    | 7                    | 4                     |
| Rb                             | 34                   | 48                   | 21                   | 35                   | 35                   | 4                    | 22                    | 39                    | 22                  | 22                   | 23                   | 5                     |
| Sr                             | 595                  | 670                  | 340                  | 575                  | 515                  | 420                  | 568                   | 1,215                 | 858                 | 670                  | 565                  | 359                   |
| Ba                             | 450                  | 600                  | 220                  | 380                  | 415                  | 148                  | 296                   | 642                   | 385                 | 296                  | 257                  | 110                   |
| Y                              | 30                   | 31                   | 23                   | 34                   | 68                   | 28                   | 23                    | 31                    | 28                  | 24                   | 27                   | 22                    |
| Zr                             | 298                  | 309                  | 169                  | 271                  | 266                  | 174                  | 236                   | 239                   | 269                 | 260                  | 211                  | 145                   |
| Nb                             | 40.7                 | 57.3                 | 20                   | 38                   | 33                   | 29                   | 46                    | 76                    | 52                  | 50                   | 51                   | 27                    |
| La                             | 41.1                 | 52.8                 | 19.7                 | 32.3                 | 53.6                 | 19.54                | 33.6                  | 49.85                 | 40.7                | 33.06                | 34.3                 | 19.07                 |
| Ce                             | 82.7                 | 105.9                | 46.2                 | 72                   | 67.6                 | 43.69                | 71.66                 | 105.67                | 87.8                | 77.31                | 73.4                 | 42.46                 |
| Nd                             | 46.3                 | 50.5                 | n.d.                 | 37.1                 | 66.4                 | 26                   | 40.13                 | 51.79                 | 44.6                | 38.85                | 32.5                 | 24.16                 |
| Sm                             | 8.9                  | 9.6                  | 5.2                  | 9.1                  | 13.6                 | 6.58                 | 7.98                  | 9.72                  | 9.21                | 7.64                 | 7.23                 | 5.09                  |
| Eu                             | 2.75                 | 2.8                  | 1.78                 | 2.84                 | 4.4                  | 2.19                 | 2.45                  | 3.25                  | 2.98                | 2.51                 | 2.34                 | 1.71                  |
| Tb                             | 1.04                 | 1.14                 | 0.71                 | 1.2                  | 1.97                 | 1.16                 | 1.04                  | 1.4                   | 1.15                | 1.07                 | 1.01                 | 0.83                  |
| Yb                             | 1.95                 | 2.23                 | 1.74                 | 2.39                 | 3.73                 | 1.9                  | 1.45                  | 2.18                  | 1.64                | 1.4                  | 1.67                 | 1.44                  |
| Lu                             | 0.29                 | 0.32                 | 0.28                 | 0.37                 | 0.56                 | 0.3                  | 0.21                  | 0.29                  | 0.22                | 0.2                  | 0.24                 | 0.22                  |
| Hf                             | 6.9                  | 7.1                  | 4.2                  | 6                    | 6.2                  | 4.55                 | 5.75                  | 4.3                   | 6.1                 | 5.82                 | 4.8                  | 3.34                  |
| Ta                             | 2.76                 | 3.61                 | 1.25                 | n.d.                 | n.d.                 | 1.72                 | 2.8                   | 5.2                   | 3.9                 | 3.3                  | 3.3                  | 1.51                  |
| Th                             | 5.8                  | 9.6                  | 3.1                  | 4                    | 3.6                  | 1.95                 | 3.6                   | 5.78                  | 4.2                 | 4.1                  | 4.1                  | 2.15                  |
| U                              | 1.23                 | 1.87                 | 0.67                 | n.d.                 | n.d.                 | 0.5                  | 1.04                  | 1.3                   | 1.1                 | 0.8                  | 0.9                  | 0.47                  |

TABLE I (continued)

|                                | 7281<br>TBA-09<br>TH | 7282<br>TBA-11<br>TH | 7300<br>TBA-115<br>BSN | 7310<br>RRT-15<br>BSN | 7314<br>RRT-32<br>TH | 7325<br>RRT-60<br>AB | 7336<br>MGA-01<br>AB | 7337<br>MGA-02<br>AB | 7338<br>MGA-10<br>AB | 7339<br>MGA-00<br>AB? | 7920<br>MGA-101<br>AB | 7921<br>MGA-102<br>BSN |
|--------------------------------|----------------------|----------------------|------------------------|-----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|-----------------------|-----------------------|------------------------|
| SiO <sub>2</sub> (wt.%)        | 42.92                | 46.46                | 44.58                  | 42                    | 45.29                | 45.87                | 44.83                | 43.56                | 43.95                | 44.6                  | 44.93                 | 44.15                  |
| Al <sub>2</sub> O <sub>3</sub> | 10.16                | 16.16                | 14.06                  | 14.6                  | 15.77                | 14.84                | 14.45                | 11.2                 | 10.1                 | 13.9                  | 16.6                  | 15.66                  |
| Fe <sub>2</sub> O <sub>3</sub> | 16.75                | 17.47                | 13.12                  | 15.9                  | 13.95                | 14.77                | 14.15                | 14.75                | 14                   | 13.65                 | 11.26                 | 13.66                  |
| MnO                            | 0.22                 | 0.27                 | 0.2                    | 0.19                  | 0.18                 | 0.2                  | 0.21                 | 0.18                 | 0.19                 | 0.15                  | 0.22                  | 0.24                   |
| MgO                            | 17.9                 | 9.27                 | 8.22                   | 6.93                  | 6.02                 | 5.5                  | 6.22                 | 10.84                | 12.7                 | 5.87                  | 3.71                  | 3.2                    |
| CaO                            | 8.79                 | 3.77                 | 11.32                  | 8.34                  | 11.32                | 7.34                 | 11.18                | 11.45                | 11.8                 | 6.7                   | 8.77                  | 8.16                   |
| Na <sub>2</sub> O              | 0.28                 | 0.3                  | 3.25                   | 4.53                  | 2.34                 | 4.37                 | 2.68                 | 2.07                 | 1.49                 | 2.47                  | 3.35                  | 4.88                   |
| K <sub>2</sub> O               | 0.19                 | 0.34                 | 1.02                   | 1.55                  | 0.29                 | 1.35                 | 0.76                 | 0.7                  | 0.45                 | 0.95                  | 1.67                  | 1.35                   |
| TiO <sub>2</sub>               | 2.92                 | 3.07                 | 2.65                   | 4.1                   | 2.79                 | 3.4                  | 3.01                 | 2.86                 | 2.67                 | 2.42                  | 2.60                  | 2.65                   |
| P <sub>2</sub> O <sub>5</sub>  | 0.23                 | 0.23                 | 0.55                   | 0.83                  | 0.33                 | 0.91                 | 0.46                 | 0.45                 | 0.42                 | 0.29                  | 0.68                  | 0.87                   |
| LOI                            | <u>0.25</u>          | <u>2.68</u>          | <u>0.45</u>            | <u>0.15</u>           | <u>1.2</u>           | <u>0.7</u>           | <u>1.41</u>          | <u>1.43</u>          | <u>1.63</u>          | <u>8.24</u>           | <u>5.92</u>           | <u>5.07</u>            |
| Total                          | 100.61               | 100.02               | 99.42                  | 99.12                 | 99.48                | 99.25                | 99.36                | 99.49                | 99.40                | 99.24                 | 99.71                 | 99.89                  |
| [Mg]                           | ~ 0.71               | 0.54                 | 0.59                   | 0.5                   | 0.49                 | 0.46                 | 0.49                 | 0.62                 | 0.67                 | 0.47                  | 0.41                  | 0.34                   |
| Li (ppm)                       | 3                    | 6                    | 9                      | 10                    | 6                    | 11                   | 9                    | 10                   | 10                   | 8                     | 15                    | 8                      |
| Rb                             | 9                    | 15                   | 27                     | 32                    | 6                    | 27                   | 19                   | 20                   | 13                   | 13                    | 32                    | 31                     |
| Sr                             | 228                  | 235                  | 647                    | 950                   | 505                  | 1,115                | 575                  | 486                  | 453                  | 343                   | 772                   | 807                    |
| Ba                             | 108                  | 502                  | 382                    | 423                   | 127                  | 406                  | 274                  | 270                  | n.d.                 | 125                   | 478                   | 434                    |
| Y                              | 26                   | 35                   | 31                     | 35                    | 24                   | 38                   | 31                   | 28                   | 27                   | 22                    | 33                    | 33                     |
| Zr                             | 198                  | 266                  | 234                    | 369                   | 157                  | 371                  | 225                  | 230                  | 207                  | 138                   | 294                   | 369                    |
| Nb                             | 62                   | 85                   | 77                     | 86                    | 28                   | 80                   | 51                   | 52                   | 43                   | 27                    | 82                    | 78                     |
| La                             | 44.34                | 61.4                 | 40.89                  | 60.04                 | 21.02                | 62.69                | 36.55                | 40.16                | 35.06                |                       | 61.8                  | 64.9                   |
| Ce                             | 90.38                | 118.3                | 101.43                 | 128.68                | 45.78                | 131.24               | 78.85                | 82.6                 | 71.92                |                       | 125.2                 | 132                    |
| Nd                             | 42.8                 | 52                   | 46.09                  | 61.57                 | 22.15                | 61.47                | 38.6                 | 39.2                 | 36.2                 |                       | 55.3                  | 60.3                   |
| Sm                             | 8.13                 | 9.75                 | 7.93                   | 12.22                 | 5.47                 | 12.1                 | 8.14                 | 8.04                 | 7.48                 |                       | 9.99                  | 11.3                   |
| Eu                             | 2.53                 | 3.06                 | 2.51                   | 3.82                  | 1.92                 | 3.81                 | 2.66                 | 2.56                 | 2.39                 |                       | 2.95                  | 3.44                   |
| Tb                             | 1.04                 | 1.37                 | 1.12                   | 1.34                  | 0.75                 | 1.3                  | 1.04                 | 0.92                 | 0.97                 |                       | 1.1                   | 1.17                   |
| Yb                             | 1.59                 | 2.78                 | 2.25                   | 2.52                  | 1.61                 | 2.76                 | 2.18                 | 1.96                 | 1.82                 |                       | 2.84                  | 2.78                   |
| Lu                             | 0.25                 | 0.41                 | 0.35                   | 0.37                  | 0.25                 | 0.41                 | 0.32                 | 0.29                 | 0.28                 |                       | 0.41                  | 0.38                   |
| Hf                             | 5.04                 | 6                    | 5.08                   | 7.55                  | 3.58                 | 7.29                 | 5.03                 | 5.16                 | 4.71                 |                       | 5.1                   | 7.2                    |
| Ta                             | 3.59                 | 5.5                  | 4.15                   | 5.8                   | 1.61                 | 5.2                  | n.d.                 | 3.31                 | 2.58                 |                       | n.d.                  | n.d.                   |
| Th                             | 5.33                 | 7.5                  | 6.84                   | 6.46                  | 2.19                 | 6.94                 | 4.32                 | 4.88                 | 3.9                  |                       | 7.4                   | 7.3                    |
| U                              | 1.3                  | 0.85                 | 1.55                   | 1.5                   | 0.59                 | 1.7                  | n.d.                 | 1.23                 | 1.15                 |                       | n.d.                  | n.d.                   |

TABLE I (continued)

|                                | 7922    | 7923     | 7924     | 7925    | 7926    | 7927     | 7928    | 7929    | 7930    | 7931    | 7932    | 7933    |
|--------------------------------|---------|----------|----------|---------|---------|----------|---------|---------|---------|---------|---------|---------|
|                                | MGA-103 | MGA-104A | MGA-104C | MGA-105 | MGA-106 | MGA-107A | MGA-108 | MGA-111 | MGA-112 | MGA-113 | MGA-116 | MGA-117 |
|                                | AB      | BSN      | BSN      | BSN     | TH      | BSN      | BSN     | BSN     | BSN     | AB      | BSN     | BSN     |
| SiO <sub>2</sub> (wt.%)        | 43.37   | 43.17    | 42.98    | 42.98   | 44.54   | 43.96    | 44.74   | 43.96   | 43.17   | 43.37   | 44.15   | 44.35   |
| Al <sub>2</sub> O <sub>3</sub> | 13.26   | 15.1     | 14.9     | 13.45   | 7.42    | 15.42    | 11.15   | 9.63    | 14      | 8.44    | 12.9    | 10.57   |
| Fe <sub>2</sub> O <sub>3</sub> | 14.3    | 14.4     | 14.4     | 16.25   | 13.4    | 14.43    | 13.02   | 12.9    | 12.8    | 14.11   | 13.13   | 13.45   |
| MnO                            | 0.21    | 0.2      | 0.2      | 0.22    | 0.19    | 0.2      | 0.19    | 0.19    | 0.21    | 0.21    | 0.21    | 0.2     |
| MgO                            | 8.98    | 6.67     | 6.78     | 6.08    | 19.52   | 5.13     | 9.63    | 11.73   | 5.6     | 17.62   | 7.13    | 12.71   |
| CaO                            | 12      | 10.97    | 10.88    | 12.28   | 10.88   | 10.16    | 14.43   | 14.45   | 12.54   | 11.15   | 13.46   | 12.23   |
| Na <sub>2</sub> O              | 2.32    | 3.25     | 3.2      | 2.69    | 1.13    | 3.88     | 2.5     | 1.95    | 3.53    | 1.67    | 2.65    | 2.74    |
| K <sub>2</sub> O               | 0.84    | 0.96     | 0.91     | 0.81    | 0.19    | 1        | 0.6     | 0.6     | 0.99    | 0.48    | 0.75    | 0.67    |
| TiO <sub>2</sub>               | 2.88    | 3.61     | 3.54     | 3.01    | 1.74    | 3.29     | 2.52    | 2.46    | 3.21    | 1.98    | 2.70    | 2.18    |
| P <sub>2</sub> O <sub>5</sub>  | 0.53    | 0.51     | 0.5      | 0.39    | 0.22    | 0.66     | 0.36    | 0.39    | 0.55    | 0.33    | 0.49    | 0.4     |
| LOI                            | 0.65    | 1.13     | 0.92     | 1       | 0.74    | 1.02     | 0.52    | 1.76    | 3.22    | 0.4     | 1.91    | 0.63    |
| Total                          | 99.34   | 99.97    | 99.21    | 99.16   | 99.97   | 99.15    | 99.66   | 100.02  | 99.85   | 99.76   | 99.48   | 100.13  |
| [Mg]                           | 0.59    | 0.51     | 0.51     | 0.46    | 0.77    | 0.44     | 0.63    | 0.67    | 0.49    | 0.74    | 0.55    | 0.68    |
| Li (ppm)                       | 9       | 11       | 12       | 8       | 9       | 9        | 5       | 7       | 6       | 6       | 9       | 6       |
| Rb                             | 19      | 21       | 20       | 17      | 5       | 24       | 15      | 15      | 22      | 11      | 19      | 16      |
| Sr                             | 584     | 637      | 645      | 496     | 234     | 664      | 404     | 429     | 637     | 340     | 553     | 440     |
| Ba                             | 305     | 357      | 370      | 297     | 110     | 342      | 195     | 228     | 328     | 196     | 289     | 241     |
| Y                              | 28      | 29       | 31       | 29      | 18      | 31       | 24      | 23      | 29      | 18      | 26      | 24      |
| Zr                             | 259     | 259      | 252      | 216     | 113     | 304      | 192     | 200     | 270     | 164     | 244     | 183     |
| Nb                             | 52      | 60       | 60       | 41      | 21      | 60       | 35      | 40      | 57      | 34      | 47      | 36.2    |
| La                             | 41.4    | 45.4     | 44.1     | 32.2    | 16.5    | 48.1     | 28.1    | 31.5    | 44.6    | 26.5    | 40.1    | 28.6    |
| Ce                             | 84.4    | 90.2     | 90.9     | 67      | 33.3    | 99       | 60.4    | 65.1    | 95.6    | 55.2    | 81      | 60.2    |
| Nd                             | 41.8    | 42.1     | 41.5     | 36.5    | 20.1    | 49       | 33.2    | 33.5    | 47.3    | 27      | 39.3    | 32.3    |
| Sm                             | 8.78    | 9.24     | 8.98     | 7.9     | 4.23    | 9.74     | 6.79    | 7.01    | 9.1     | 5.54    | 8.17    | 6.2     |
| Eu                             | 2.66    | 2.85     | 2.87     | 2.48    | 1.38    | 2.98     | 2.16    | 2.18    | 2.89    | 1.76    | 2.55    | 1.96    |
| Tb                             | 1.01    | 1.04     | 0.99     | 0.95    | 0.66    | 1.1      | 0.87    | 0.82    | 1.09    | 0.67    | 1.04    | 0.82    |
| Yb                             | 2.17    | 2.28     | 2.22     | 2.08    | 1.09    | 2.46     | 1.75    | 1.56    | 2.27    | 1.38    | 2.1     | 1.66    |
| Lu                             | 0.31    | 0.34     | 0.32     | 0.31    | 0.18    | 0.36     | 0.26    | 0.23    | 0.34    | 0.21    | 0.32    | 0.25    |
| Hf                             | 5.3     | 5.1      | 5.1      | 4.6     | 2.5     | 6.1      | 4.2     | 4.4     | 5.6     | 3.5     | 5.1     | 3.7     |
| Ta                             | n.d.    | n.d.     | n.d.     | n.d.    | n.d.    | n.d.     | n.d.    | n.d.    | n.d.    | n.d.    | n.d.    | 2.37    |
| Th                             | 4.7     | 5.5      | 5.5      | 3.5     | 1.7     | 5.8      | 3       | 3.6     | 5.2     | 2.9     | 4.3     | 3.2     |
| U                              | n.d.    | n.d.     | n.d.     | n.d.    | n.d.    | n.d.     | n.d.    | n.d.    | n.d.    | n.d.    | nd.     | 0.93    |

TABLE I (continued)

|                                | 7934<br>MGA-118<br>BSN | 7935<br>ATU102<br>AB | 7936<br>ATU104<br>AB | 7937<br>ATU111<br>BSN | 7938<br>ATU113<br>BSN | 7939<br>ATU114<br>AB | 7940<br>ATU115<br>BSN | 7941<br>ATU123<br>AB | 7942<br>ATU127<br>AB | 7943<br>ATU128<br>AB | 7944<br>ATU132<br>BSN | 7945<br>ATU133<br>AB |
|--------------------------------|------------------------|----------------------|----------------------|-----------------------|-----------------------|----------------------|-----------------------|----------------------|----------------------|----------------------|-----------------------|----------------------|
| SiO <sub>2</sub> (wt.%)        | 44.35                  | 47.1                 | 45.88                | 45.38                 | 45.48                 | 43.86                | 45.2                  | 44.47                | 45.68                | 44.87                | 44.97                 | 43.86                |
| Al <sub>2</sub> O <sub>3</sub> | 16.18                  | 15.6                 | 15.32                | 16.17                 | 15.58                 | 8.57                 | 15.08                 | 10.05                | 15.1                 | 10.4                 | 14.5                  | 9.47                 |
| Fe <sub>2</sub> O <sub>5</sub> | 12.9                   | 11.76                | 11.72                | 11.5                  | 11.4                  | 13.18                | 12.58                 | 12.6                 | 12.07                | 12.6                 | 12.32                 | 14.2                 |
| MnO                            | 0.22                   | 0.19                 | 0.2                  | 0.17                  | 0.18                  | 0.19                 | 0.18                  | 0.17                 | 0.17                 | 0.17                 | 0.18                  | 0.2                  |
| MgO                            | 3.88                   | 4.84                 | 5.14                 | 4.3                   | 5.17                  | 18.3                 | 5.28                  | 14.16                | 5.15                 | 15.08                | 6.1                   | 16.03                |
| CaO                            | 10.05                  | 10.34                | 10.23                | 10.2                  | 10.95                 | 9.27                 | 10.7                  | 10.34                | 10.34                | 9.29                 | 11.2                  | 10.45                |
| Na <sub>2</sub> O              | 4.8                    | 3.6                  | 3.17                 | 4.05                  | 3.32                  | 1.87                 | 3.3                   | 1.98                 | 3.42                 | 2.41                 | 3.2                   | 2.04                 |
| K <sub>2</sub> O               | 1.44                   | 1.38                 | 1.28                 | 1.7                   | 1.53                  | 0.74                 | 1.5                   | 0.85                 | 1.54                 | 0.9                  | 1.34                  | 0.7                  |
| TiO <sub>2</sub>               | 2.93                   | 3.19                 | 3.25                 | 3.21                  | 3.1                   | 2.16                 | 3.17                  | 2.19                 | 3.15                 | 2.35                 | 2.89                  | 2.15                 |
| P <sub>2</sub> O <sub>5</sub>  | 0.7                    | 0.65                 | 0.62                 | 0.67                  | 0.63                  | 0.4                  | 0.6                   | 0.36                 | 0.59                 | 0.37                 | 0.56                  | 0.37                 |
| LOI                            | 1.91                   | 1.4                  | 2.47                 | 2.17                  | 2.6                   | 1.21                 | 1.57                  | 2.97                 | 2.38                 | 1.09                 | 1.88                  | 0.69                 |
| Total                          | 99.36                  | 100.05               | 99.28                | 99.52                 | 99.94                 | 99.75                | 99.16                 | 100.14               | 99.59                | 99.53                | 99.14                 | 100.16               |
| [Mg]                           | 0.40                   | 0.48                 | 0.49                 | 0.45                  | 0.5                   | 0.76                 | 0.48                  | 0.71                 | 0.48                 | 0.73                 | 0.52                  | 0.72                 |
| Li (ppm)                       | 10                     | 8                    | 8                    | 7                     | 8                     | 6                    | 8                     | 5                    | 10                   | 6                    | 10                    | 6                    |
| Rb                             | 30                     | 35                   | 33                   | 46                    | 41                    | 21                   | 41                    | 19                   | 43                   | 26                   | 38                    | 22                   |
| Sr                             | 801                    | 686                  | 670                  | 766                   | 766                   | 434                  | 705                   | 433                  | 659                  | 405                  | 704                   | 409                  |
| Ba                             | 448                    | 383                  | 373                  | 515                   | 444                   | 258                  | 430                   | 215                  | 411                  | 219                  | 413                   | 237                  |
| Y                              | 31                     | 31                   | 30                   | 35                    | 30                    | 20                   | 31.4                  | 22                   | 30                   | 21.9                 | 28                    | 23.2                 |
| Zr                             | 345                    | 288                  | 281                  | 323                   | 293                   | 182                  | 299                   | 188                  | 291                  | 185                  | 289                   | 178                  |
| Nb                             | 71                     | 57                   | 56                   | 71                    | 61                    | 35                   | 64                    | 33                   | 60                   | 33.7                 | 57                    | 34.5                 |
| La                             | 57.2                   | 49.8                 |                      |                       |                       | 32.4                 | 51.7                  |                      |                      | 30.8                 |                       | 27.7                 |
| Ce                             | 121.7                  | 101.7                |                      |                       |                       | 64.2                 | 105.9                 |                      |                      | 64                   |                       | 57.8                 |
| Nd                             | 55.9                   | 49.3                 |                      |                       |                       | 28.3                 | 48.9                  |                      |                      | 27.5                 |                       | 28                   |
| Sm                             | 10.34                  | 9.72                 |                      |                       |                       | 5.9                  | 9.46                  |                      |                      | 5.85                 |                       | 5.95                 |
| Eu                             | 3.28                   | 2.92                 |                      |                       |                       | 1.76                 | 2.8                   |                      |                      | 1.75                 |                       | 1.81                 |
| Tb                             | 1.2                    | 1.34                 |                      |                       |                       | 0.84                 | 1.28                  |                      |                      | 0.81                 |                       | 0.82                 |
| Yb                             | 2.69                   | 2.33                 |                      |                       |                       | 1.43                 | 2.46                  |                      |                      | 1.58                 |                       | 1.52                 |
| Lu                             | 0.39                   | 0.34                 |                      |                       |                       | 0.19                 | 0.36                  |                      |                      | 0.23                 |                       | 0.23                 |
| Hf                             | 6.4                    | 5.6                  |                      |                       |                       | 3.5                  | 5.8                   |                      |                      | 4                    |                       | 3.8                  |
| Ta                             | n.d.                   | 4.1                  |                      |                       |                       | 2.4                  | 4.08                  |                      |                      | 2.01                 |                       | 2.15                 |
| Th                             | 7.1                    | 6                    |                      |                       |                       | 3.6                  | 6.4                   |                      |                      | 3.9                  |                       | 3.2                  |
| U                              | n.d.                   | 1.5                  |                      |                       |                       | 0.87                 | 1.67                  |                      |                      | 0.93                 |                       | 0.83                 |



TABLE I (continued)

|                                | 7983<br>ATT102<br>NE | 7984<br>ATT103<br>NE | 7985<br>ATT104<br>NE | 7986<br>ATT106<br>NE | 7987<br>ATT108<br>BSN | 7988<br>ATT119<br>NE | 7989<br>ATT121<br>NE | 7990<br>ATT122<br>NE | 7991<br>ATT123<br>NE | 7992<br>ATT125<br>NE | 7993<br>ATT126<br>NE | 7994<br>ATT127<br>BSN |
|--------------------------------|----------------------|----------------------|----------------------|----------------------|-----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|-----------------------|
| SiO <sub>2</sub> (wt.%)        | 39.24                | 40.58                | 39.81                | 39.05                | 45.37                 | 39.63                | 40.12                | 39.24                | 40.42                | 39.25                | 41.22                | 41.8                  |
| Al <sub>2</sub> O <sub>3</sub> | 10.46                | 11.16                | 11                   | 11.07                | 16                    | 11.25                | 11.2                 | 11.11                | 11.07                | 11                   | 11.6                 | 11.3                  |
| Fe <sub>2</sub> O <sub>3</sub> | 13.15                | 12.88                | 12.74                | 12.9                 | 13.4                  | 12.6                 | 12.62                | 13.07                | 12.52                | 12.62                | 12.83                | 12.75                 |
| MnO                            | 0.19                 | 0.19                 | 0.2                  | 0.19                 | 0.2                   | 0.19                 | 0.19                 | 0.19                 | 0.19                 | 0.29                 | 0.2                  | 0.19                  |
| MgO                            | 11.15                | 10.44                | 10.77                | 11.6                 | 4.48                  | 11.6                 | 11.63                | 12.05                | 11.6                 | 12.16                | 11.8                 | 11.24                 |
| CaO                            | 13.32                | 12.12                | 12.48                | 11.86                | 9.2                   | 12.48                | 11.87                | 12.4                 | 11.86                | 12.34                | 12                   | 11.9                  |
| Na <sub>2</sub> O              | 4.12                 | 4.05                 | 4.57                 | 4.7                  | 3.88                  | 3.92                 | 4.97                 | 4.7                  | 4.2                  | 4.13                 | 3.7                  | 3.3                   |
| K <sub>2</sub> O               | 1.92                 | 1.85                 | 2.07                 | 2.15                 | 1.43                  | 1.8                  | 2.32                 | 2.1                  | 1.9                  | 1.72                 | 1.11                 | 1.38                  |
| TiO <sub>2</sub>               | 2.63                 | 2.64                 | 2.58                 | 2.58                 | 3.25                  | 2.5                  | 2.5                  | 2.54                 | 2.53                 | 2.43                 | 2.25                 | 2.29                  |
| P <sub>2</sub> O <sub>5</sub>  | 1.01                 | 1.07                 | 1.09                 | 1.11                 | 0.81                  | 1.05                 | 1.03                 | 1.11                 | 1.09                 | 1.11                 | 1.16                 | 1.2                   |
| LOI                            | <u>2.22</u>          | <u>2.17</u>          | <u>1.94</u>          | <u>1.96</u>          | <u>1.01</u>           | <u>2.12</u>          | <u>0.69</u>          | <u>0.86</u>          | <u>1.76</u>          | <u>2.48</u>          | <u>1.6</u>           | <u>2.12</u>           |
| Total                          | 99.41                | 99.15                | 99.25                | 99.17                | 99.03                 | 99.14                | 99.14                | 99.37                | 99.14                | 99.53                | 99.47                | 99.39                 |
| [Mg]                           | 0.65                 | 0.64                 | 0.65                 | 0.67                 | 0.43                  | 0.67                 | 0.67                 | 0.67                 | 0.67                 | 0.68                 | 0.67                 | 0.66                  |
| Li (ppm)                       | 17                   | 18                   | 17                   | 17                   | 10                    | 16                   | 18                   | 14                   | 17                   | 16                   | 16                   | 16                    |
| Rb                             | 46                   | 44                   | 48                   | 51                   | 35                    | 46                   | 55                   | 49                   | 45                   | 43                   | 17                   | 62                    |
| Sr                             | 1,023                | 1,079                | 1,163                | 984                  | 943                   | 1,626                | 1,423                | 1,245                | 1,440                | 1,278                | 1,248                | n.d.                  |
| Ba                             | 312                  | 284                  | 633                  | 1,364                | 533                   | 1,020                | 619                  | 626                  | 779                  | 718                  | 1,096                | 1,262                 |
| Y                              | 30                   | 33                   | 32                   | 33                   | 34                    | 32                   | 35                   | 31                   | 31                   | 31                   | 33                   | 35                    |
| Zr                             | 290                  | 303                  | 305                  | 295                  | 315                   | 357                  | 342                  | 311                  | 330                  | 311                  | 284                  | 347                   |
| Nb                             | 78                   | 79                   | 78                   | 81                   | 57                    | 82                   | 86                   | 75                   | 79                   | 74                   | 75                   | 75                    |
| La                             |                      |                      |                      |                      | 51.4                  |                      |                      | 87                   |                      |                      |                      |                       |
| Ce                             |                      |                      |                      |                      | 108.3                 |                      |                      | 160.7                |                      |                      |                      |                       |
| Nd                             |                      |                      |                      |                      | 51.1                  |                      |                      | 73.8                 |                      |                      |                      |                       |
| Sm                             |                      |                      |                      |                      | 10.06                 |                      |                      | 13.31                |                      |                      |                      |                       |
| Eu                             |                      |                      |                      |                      | 3.08                  |                      |                      | 4.02                 |                      |                      |                      |                       |
| Tb                             |                      |                      |                      |                      | 1.32                  |                      |                      | 1.69                 |                      |                      |                      |                       |
| Yb                             |                      |                      |                      |                      | 2.61                  |                      |                      | 1.78                 |                      |                      |                      |                       |
| Lu                             |                      |                      |                      |                      | 0.38                  |                      |                      | 0.246                |                      |                      |                      |                       |
| Hf                             |                      |                      |                      |                      | 5.7                   |                      |                      | 4.7                  |                      |                      |                      |                       |
| Ta                             |                      |                      |                      |                      | n.d.                  |                      |                      | 4.7                  |                      |                      |                      |                       |
| Th                             |                      |                      |                      |                      | 6                     |                      |                      | 15.6                 |                      |                      |                      |                       |
| U                              |                      |                      |                      |                      | n.d.                  |                      |                      | 2.8                  |                      |                      |                      |                       |

TABLE I (continued)

|                                | 7995<br>ATT131<br>NE | 7996<br>ATT132<br>NE | 7997<br>AFT136<br>BSN | 7998<br>ATT138<br>NE | 7999<br>ATT139<br>BSN | 8000<br>ATT144<br>BSN | 8001<br>ATT145<br>BSN | 8002<br>ATT146<br>BSN | 8003<br>ATT148<br>BSN | 8004<br>ATT149<br>BSN | 8005<br>ATT149X<br>NE | 8006<br>ATT152<br>NE | 8007<br>ATT154<br>NE |
|--------------------------------|----------------------|----------------------|-----------------------|----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|----------------------|----------------------|
| SiO <sub>2</sub>               | 41.03                | 41.52                | 41.33                 | 40.64                | 45.62                 | 45.13                 | 44.94                 | 45.32                 | 44.93                 | 44.93                 | 39.5                  | 41.22                | 39.76                |
| Al <sub>2</sub> O <sub>3</sub> | 11.41                | 11.38                | 11.17                 | 11.33                | 11.27                 | 11.5                  | 11.35                 | 11.46                 | 11.71                 | 11.57                 | 11.07                 | 11.45                | 11.12                |
| Fe <sub>2</sub> O <sub>3</sub> | 13.3                 | 13.07                | 12.75                 | 12.8                 | 11.83                 | 11.95                 | 12.04                 | 12.02                 | 12                    | 11.91                 | 14.06                 | 13                   | 14.05                |
| MnO                            | 0.19                 | 0.19                 | 0.19                  | 0.19                 | 0.16                  | 0.16                  | 0.16                  | 0.16                  | 0.16                  | 0.16                  | 0.21                  | 0.2                  | 0.2                  |
| MgO                            | 11.12                | 11.45                | 11.66                 | 12.18                | 12.86                 | 12.26                 | 11.95                 | 11.55                 | 11.58                 | 11.93                 | 10.9                  | 11.31                | 10.58                |
| CaO                            | 11.56                | 11.8                 | 11.83                 | 12.1                 | 9.85                  | 10.05                 | 10.2                  | 9.94                  | 10                    | 10                    | 12.56                 | 11.75                | 11.66                |
| Na <sub>2</sub> O              | 4.2                  | 3.92                 | 3.34                  | 3.37                 | 2.16                  | 3.21                  | 4                     | 3.87                  | 3.13                  | 3.9                   | 4.45                  | 3.75                 | 4.67                 |
| K <sub>2</sub> O               | 1.52                 | 1.34                 | 1.29                  | 1.33                 | 1.06                  | 0.7                   | 1.11                  | 0.94                  | 0.6                   | 0.87                  | 1.45                  | 1.5                  | 1.2                  |
| TiO <sub>2</sub>               | 2.3                  | 2.23                 | 2.2                   | 2.21                 | 2                     | 2.15                  | 2.13                  | 2.13                  | 2.14                  | 2.06                  | 2.35                  | 2.19                 | 2.58                 |
| P <sub>2</sub> O <sub>5</sub>  | 1.05                 | 1.01                 | 1.05                  | 1.07                 | 0.64                  | 0.68                  | 0.65                  | 0.67                  | 0.64                  | 0.65                  | 1.03                  | 1.08                 | 1.17                 |
| LOI                            | <u>1.52</u>          | <u>1.23</u>          | <u>2.32</u>           | <u>1.95</u>          | <u>2.19</u>           | <u>1.8</u>            | <u>0.7</u>            | <u>1.41</u>           | <u>2.43</u>           | <u>1.18</u>           | <u>1.5</u>            | <u>1.65</u>          | <u>2.13</u>          |
| Total                          | 99.2                 | 99.14                | 99.13                 | 99.17                | 99.64                 | 99.59                 | 99.23                 | 99.47                 | 99.32                 | 99.16                 | 99.08                 | 99.1                 | 99.12                |
| [Mg]                           | 0.65                 | 0.66                 | 0.67                  | 0.68                 | 0.71                  | 0.69                  | 0.69                  | 0.68                  | 0.68                  | 0.69                  | 0.63                  | 0.66                 | 0.62                 |
| Li (ppm)                       | 12                   | 9                    | 15                    | 11                   | 9                     | 10                    | 10                    | 10                    | 10                    | 9                     | 17                    | 14                   | 15                   |
| Rb                             | 50                   | 48                   | 48                    | 54                   | 16                    | 31                    | 60                    | 70                    | 28                    | 25                    | 47                    | 46                   | 63                   |
| Sr                             | 1,227                | 1,538                | n.d.                  | 1,294                | 794                   | 858                   | 843                   | 856                   | 886                   | 850                   | 1,514                 | 1,206                | 1,413                |
| Ba                             | 1,185                | 1,188                | 1,073                 | 853                  | 845                   | 752                   | 744                   | 758                   | 762                   | 736                   | 1,324                 | 1,207                | 1,332                |
| Y                              | 33                   | 35                   | 34                    | 35                   | 23                    | 24                    | 28                    | 26                    | 24                    | 24                    | 33                    | 32                   | 32                   |
| Zr                             | 284                  | 305                  | 363                   | 272                  | 210                   | 230                   | 227                   | 231                   | 239                   | 232                   | 341                   | 267                  | 321                  |
| Nb                             | 76                   | 73                   | 76                    | 74                   | 46                    | 51                    | 50                    | 50                    | 54                    | 53                    | 97                    | 73                   | 91                   |
| La                             |                      | 99.1                 |                       |                      |                       |                       | 45.1                  |                       |                       | 44.4                  | 112.3                 |                      |                      |
| Ce                             |                      | 176.6                |                       |                      |                       |                       | 85.8                  |                       |                       | 85.4                  | 206                   |                      |                      |
| Nd                             |                      | 76.4                 |                       |                      |                       |                       | 37.6                  |                       |                       | 38.8                  | 86.3                  |                      |                      |
| Sm                             |                      | 13.3                 |                       |                      |                       |                       | 8.08                  |                       |                       | 7.91                  | 14.59                 |                      |                      |
| Eu                             |                      | 4.06                 |                       |                      |                       |                       | 2.61                  |                       |                       | 2.62                  | 4.42                  |                      |                      |
| Tb                             |                      | 1.74                 |                       |                      |                       |                       | 1.06                  |                       |                       | 1.06                  | 1.9                   |                      |                      |
| Yb                             |                      | 1.9                  |                       |                      |                       |                       | 1.43                  |                       |                       | 1.36                  | 1.76                  |                      |                      |
| Lu                             |                      | 0.266                |                       |                      |                       |                       | 0.2                   |                       |                       | 0.197                 | 0.244                 |                      |                      |
| Hf                             |                      | 4.1                  |                       |                      |                       |                       | 3.8                   |                       |                       | 3.7                   | 5.1                   |                      |                      |
| Ta                             |                      | n.d.                 |                       |                      |                       |                       | n.d.                  |                       |                       | n.d.                  | n.d.                  |                      |                      |
| Th                             |                      | 18.9                 |                       |                      |                       |                       | 8.2                   |                       |                       | 8.1                   | 22.8                  |                      |                      |
| U                              |                      | n.d.                 |                       |                      |                       |                       | n.d.                  |                       |                       | n.d.                  | n.d.                  |                      |                      |

Samples from *Marquesas Islands*: EAO=Eiao, UAP and UP=Ua Pou, FTK=Fatu Huku; *Society Islands*: MAP=Moua Pihaa Seamount, ME=Mehetia, THT=Tahiti, RA=Raiatea, TA=Tahaa, BB=Bora Bora; *Austral-Cook Islands*: MCD=Macdonald Seamount, MRT=Marotiri, RA and RPA=Rapa, RVV=Raivavae, TBA=Tubuai, RRT=Rurutu, MGA=Mangaia, ATU=Atiu, ATT=Aitutaki. Other analyses have been published. *Society Islands*: Dostal et al. (1982); *Marquesas Islands*: Liotard et al. (1986); *Austral Islands*: Dupuy et al. (1988). TH=tholeiite; AB=alkali basalt; BSN=basanite; NE=nephelinite; LOI=loss on ignition; [Mg]-value=Mg/(Mg+Fe<sub>tot</sub>); n.d.=not determined.

with higher Ba/Nb ratios (Ba/Nb=9–13) and AC basalts with lower Ba/Nb ratios (Ba/Nb=4–7). However, the lowest Ba/Nb ratios (Ba/Nb=1.3–5) are found in quartz tholeiites from Ua Pou of the MA Islands, which are distinctly separated from other MA basalts. This discrimination is also apparent in the isotopic systems; in a graph of  $\epsilon_{Nd}$  vs.  $\epsilon_{Sr}$  these Ua Pou tholeiites plot close to Tubuai basalts (Duncan et al., 1986; Dupuy et al., 1987). On the other hand the Tubuai basalts share the same Ba/Nb values with those from the other AC but differ by lower Sr/Ce and Zr/Nb (Dupuy et al., 1988).

The chemical composition of the SO basalts closely resembles that of most of the MA basalts as is shown by (among other features) the similarities of their ITE patterns (Fig. 2) and the corresponding element ratios (Table II). However, the SO Islands differ from the AC Islands by the absence of basalts which contain long-term high U/Pb ratios (HIMU; Zindler and Hart, 1986). The basalts from the Cook Is-

lands are usually silica-undersaturated. On two of the Cook Islands, Mangaia and Atiu, the normative nepheline content of the basalts varies from 2% to 9% whereas on another island, Aitutaki, basalts with nepheline contents of <9% are scarce. On the latter island, basalts are strongly undersaturated (normative nepheline=14–23%) and correspond to nephelinites and leucite-nephelinites. The degree of differentiation reflected by the [Mg]-value varies at Mangaia and Atiu between 0.73 and 0.42, suggesting that these basalts, like those of most other island chains, have undergone low-pressure fractionation. On the other hand, at Aitutaki, all nephelinites are rather primitive with [Mg]-values ranging between 0.70 and 0.63.

At Mangaia and Atiu, the ITE contents increase with differentiation and on both islands their concentrations and ratios are the same, with exception of  $K_2O$  which is higher at Atiu. The alkali basalts of Aitutaki display geochemical features similar to those from Mangaia and Atiu whereas the nephelinites of Aitutaki are more enriched in ITE, thus reflecting their higher degree of undersaturation. The ITE ratios are similar to those obtained at Mangaia and Atiu with the exception of ratios involving Th which result in lower Nb/Th and higher Th/La values (Th/La=0.17–0.20) on Aitutaki. Such high values as well as the petrography of the corresponding basalts resemble those of the Tubuai nephelinites (Dupuy et al., 1988). The ITE patterns and concentrations in the basalts from these three islands of the Cook archipelago resemble AC basalts. These similarities extend even to isotopic ratios (Vidal et al., 1984; Palacz and Saunders, 1986).

In spite of the compositional variations which reflect mantle heterogeneities in southern Polynesia (Vidal et al., 1984), the basalts from the MA, AC and SO may be subdivided into two main types:

(1) Type 1 (Fig. 2a) has an ITE pattern with a distinct depletion in Rb, K, Ba and Sr, and its shape is antipathetic to that of island arc tholeiites (IAT) (Dupuy et al., 1988). Such a pat-

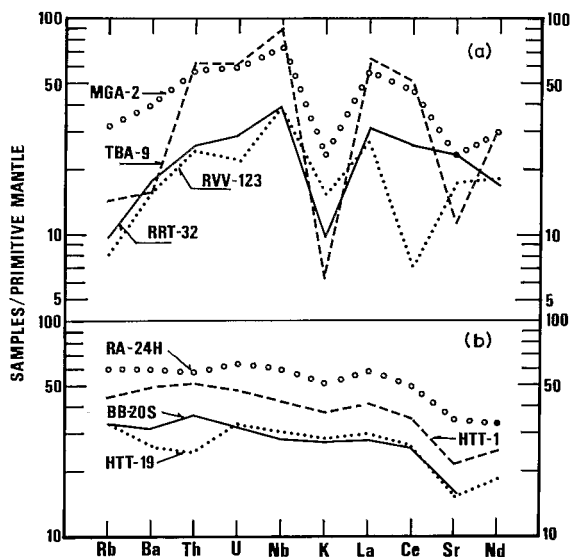


Fig. 2. Incompatible trace-element abundances normalized to primitive mantle (normalizing values from Sun and McDonough, 1989) for the different archipelagos. a. AC=Austral-Cook Islands (MGA=Mangaia; TBA=Tubuai; RRT=Rurutu; RVV=Raivavae). b. SO=Society Islands (RA=Raiatea; BB=Bora Bora). MA=Marquesas Islands (HTT=Hatutu).

TABLE II

Averaged incompatible trace-element (ITE) ratios in the different archipelagos calculated from a selection of basalts

| Archipelago                       |           | Ba/La    | Nb/La   | Nb/Th   | Rb/Ce | Nb/U               | Sr/Nd | Nb/Ta | Hf/Sm   | Zr/Sm | Sm/Nd | Rb/Sr       |
|-----------------------------------|-----------|----------|---------|---------|-------|--------------------|-------|-------|---------|-------|-------|-------------|
| Austral-Cook (a)<br>(HIMU)        | <i>n</i>  | 30       | 30      | 30      | 30    | 6                  | 30    | 6     | 30      | 30    | 30    | 30          |
|                                   | $\bar{x}$ | 7.4      | 1.35    | 11.4    | 0.21  | 45.0               | 14.3  | 16.8  | 0.63    | 27.6  | 0.201 | 0.031       |
|                                   | <i>s</i>  | 0.8      | 0.13    | 0.9     | 0.06  | 4.5                | 1.9   | 1.3   | 0.05    | 1.9   | 0.013 | 0.008       |
| Austral-Cook (b)<br>(not HIMU)    | <i>n</i>  | 26       | 25      | 25      | 25    | 8                  | 25    | 9     | 26      | 25    | 26    | 24          |
|                                   | $\bar{x}$ | 8.4      | 1.42    | 12.5    | 0.28  | 59.6               | 16.4  | 16.5  | 0.68    | 29.5  | 0.208 | 0.032       |
|                                   | <i>s</i>  | 1.4      | 0.11    | 1.2     | 0.06  | 12.0               | 2.3   | 1.4   | 0.05    | 2.4   | 0.019 | 0.007       |
| Marquesas                         | <i>n</i>  | 19       | 18      | 18      | 16    | 10                 | 18    | 10    | 19      | 17    | 19    | 16          |
|                                   | $\bar{x}$ | 10.6     | 1.03    | 8.3     | 0.36  | 38.1               | 14.9  | 14.7  | 0.66    | 29.6  | 0.222 | 0.045       |
|                                   | <i>s</i>  | 1.4      | 0.09    | 1.1     | 0.14  | 8.4                | 0.9   | 0.6   | 0.05    | 1.6   | 0.034 | 0.020       |
| Society                           | <i>n</i>  | 20       | 21      | 22      | 21    | 7                  | 18    | 7     | 22      | 21    | 20    | 21          |
|                                   | $\bar{x}$ | 10.9     | 1.05    | 7.6     | 0.40  | 34.9* <sup>1</sup> | 14.7  | 15.9  | 0.69    | 29.3  | 0.214 | 0.051       |
|                                   | <i>s</i>  | 1.3      | 0.17    | 1.8     | 0.12  | 9.1                | 2.3   | 0.8   | 0.07    | 2.8   | 0.014 | 0.021       |
| Primitive<br>mantle* <sup>2</sup> |           | 9.6-10.0 | 1.0-1.2 | 8.6-9.6 | 0.37  | 30-35              | 16-17 | 17.5  | 0.68-74 | 25-29 | 0.32  | 0.028-0.031 |

\*<sup>1</sup>32 (*s* = 14) (Hofmann et al., 1986).\*<sup>2</sup>Compiled from Jagoutz et al. (1979), Taylor (1980), Sun (1982) and Jochum et al. (1986).

Differentiated samples ( $[Mg] < 0.45$ ) as well as samples with anomalously scattered ratios which generally reflect secondary alteration processes (as seen for example in MAP, Table I) are excluded. The AC Islands have been subdivided in two groups according to their Sr and Nd isotope ratios: group (a) refers to basalts from islands which display typical HIMU characteristics (Tubuai, Rurutu, Mangaia, Raivavae); and group (b) refers to the basalts of the other islands (Macdonald, Marotiri, Rapa). Their averaged ratios for ITE do not show noticeable differences. *n* = number of samples;  $\bar{x}$  = mean; *s* = standard deviation.

tern is not only encountered in basalts from the AC Islands of Tubuai and Mangaia but also in the tholeiites from Ua Pou from the MA Islands which all display HIMU characteristics. In addition, a depletion of alkali and alkali-earth elements is present in other AC basalts. Such patterns are also typical for basalts from St. Helena in the Atlantic Ocean (Weaver et al., 1986) and from Tahalra in the Hoggar (West Africa) (Dautria et al., 1988). In fact, the basalts from these different environments – oceanic and continental – share common geochemical features: most contain HIMU components and display the same ITE distribution marked by a positive anomaly in Nb.

(2) Type 2 is marked by the absence of negative Ba anomalies and chondritic values for Ba/Nb (Fig. 2b). Some samples have a flat pattern in the range from Rb to Nb. These patterns are predominant in MA and SO basalts and are only rarely observed in AC basalts where they are limited to a few basalts from Rimatara and Marotiri (Dupuy et al., 1988).

The differences between the two groups are also shown by the average element ratios in Table II and Fig. 3. In addition to Ba/Nb, several other ratios differ between these two groups. The ratios include Nb/La, Nb/U and Nb/Th, which are higher, and Ba/La and Rb/Ce, which are lower in AC basalts. The few available Pb determinations (Vidal et al., 1984; Palacz and Saunders, 1986; Dupuy et al., 1987; Rocaboy et al., 1988) indicate that Pb/Ce follows the Ba/La ratio and thus also discriminates between the two types of basalts. It appears that the mantle source of AC basalts, compared to that of MA and SO lavas, is more depleted in Ba, Pb, Rb and Sr relative to LREE, and, in addition, Rb is more depleted relative to Sr. These basalts have element ratios generally similar to those of mid-ocean ridge basalts (MORB) (e.g., Fig. 3) while MA and SO basalts have ratios close to chondrites. Some other ratios have similar values in the different island chains. The ratios of Nb/Ta, Hf/Sm and Zr/Sm in all analyzed basalts seem to vary only within the range

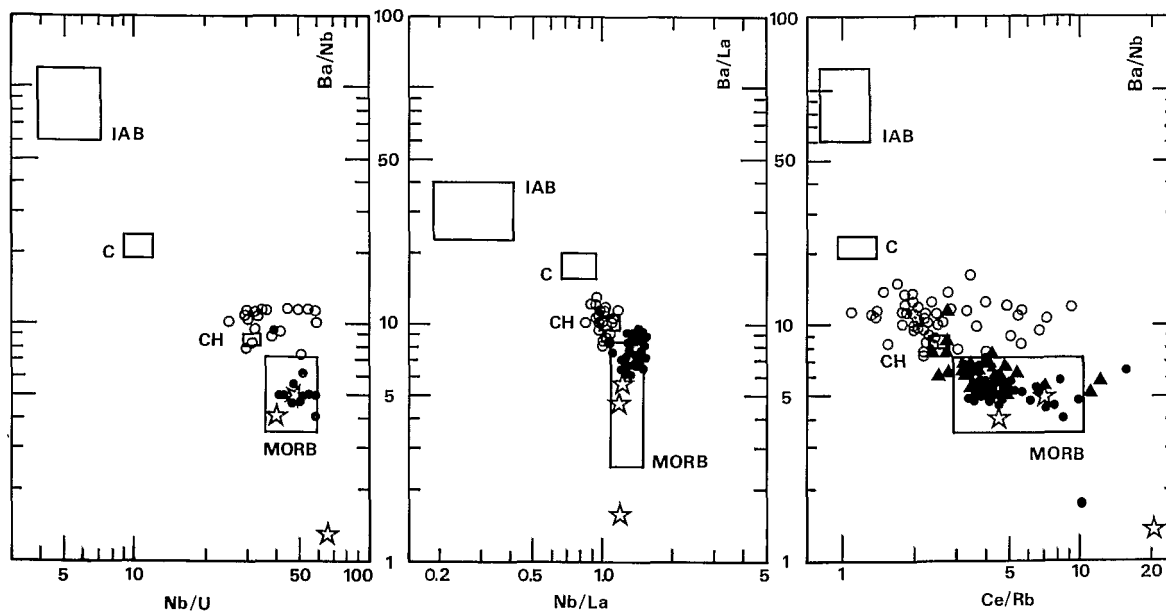


Fig. 3. Ba/Nb vs. Nb/U, Ba/La vs. Nb/La and Ba/Nb vs. Ce/Rb in basalts from the different archipelagos. *Open circles*=Marquesas and Society basalts; *open stars*=Ua Pou tholeiites; *solid circles*=Austral basalts; in (a) and (b). In (c), the Austral basalts are subdivided into the rocks with (*solid circles*) and without (*solid triangles*) HIMU characteristics (Table II). *IAB*=island-arc basalts [data from Ewart and Hawkesworth (1987), and Ryerson and Watson (1987)]; *C*=continental crust (Taylor and McLennan, 1985) and oceanic sediments (White et al., 1985); *CH*=chondrites (Sun and McDonough, 1989); *MORB*=our compilation based mainly on data from Wood et al. (1979a, b), and Sun et al. (1979); Nb/U from Hofmann et al. (1988).

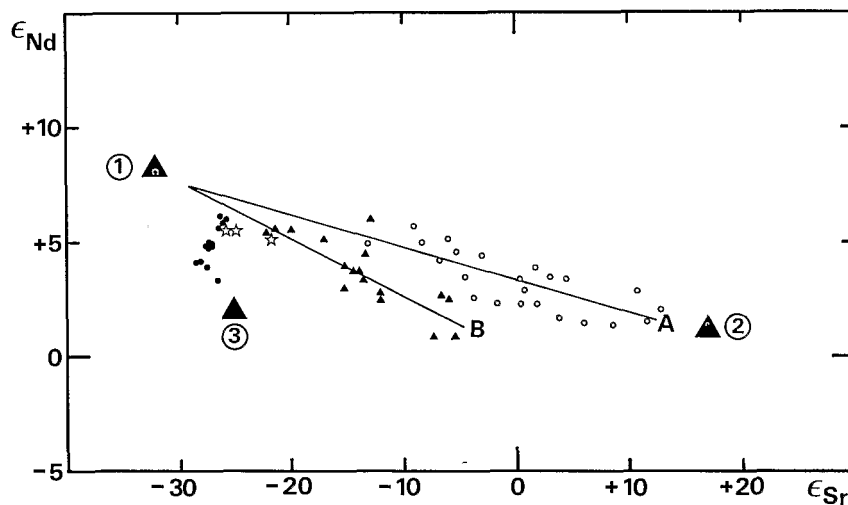


Fig. 4.  $\epsilon_{Nd}$  vs.  $\epsilon_{Sr}$  for Marquesas basalts (*open symbols*) [data from Dupuy et al. (1987), Duncan et al. (1986)], and Austral-Cook basalts (*solid symbols*) [data from Vidal et al. (1984), Chauvel et al. (1986), Palacz and Saunders (1986), Tatsumoto et al. (1983)]. *Solid circles* and *open stars* represent basalts with HIMU characteristics. *Triangles* represent present-day  $\epsilon_{Nd}$  and  $\epsilon_{Sr}$  for: ① underlying harzburgite; ② altered oceanic crust; and ③ refractory oceanic crust after dehydration and partial melting during subduction. *A*=correlation line for Marquesas basalts (excepted tholeiites from Ua Pou); *B*=correlation line for Austral-Cook basalts (excepted basalts with HIMU components). Note that these two lines cross at a point close to the composition of harzburgite, suggesting the presence of the same depleted ultramafic end-member in the different archipelagos.

of analytical error and display chondritic and/or primitive upper-mantle values (Table II). It is noteworthy that similar trace-element differences among OIB have been observed in islands from the South Atlantic (Weaver et al., 1986).

The isotopic data also delineate the two groups of island chains in southern Polynesia. In Fig. 4, the MA basalts differ from AC basalts by higher  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios for a given value of  $^{143}\text{Nd}/^{144}\text{Nd}$ . The AC basalts enriched in radiogenic Pb (e.g., Tubuai and Mangaia; Vidal et al., 1984; Dupré et al., 1985; Palacz and Saunders, 1986) are characterized by lower  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios for given values of  $^{143}\text{Nd}/^{144}\text{Nd}$  compared to the other AC lavas. Several ITE ratios tend to correlate either with  $^{87}\text{Sr}/^{86}\text{Sr}$  or  $^{143}\text{Nd}/^{144}\text{Nd}$ . The correlations of  $^{87}\text{Sr}/^{86}\text{Sr}$  vs. Rb/Sr have already been reported from Polynesian basalts (Duncan and Compston, 1976; Matsuda et al., 1984). The correlations including  $^{87}\text{Sr}/^{86}\text{Sr}$  vs. Ba/La or  $^{143}\text{Nd}/^{144}\text{Nd}$  vs. Ba/Nb in OIB and MORB are usually attributed to a mixing process (e.g., Zindler et al., 1984). Some of these correlation graphs for the basalts of southern Polynesia also tend to define the two groups of island chains (e.g., Fig. 5). The same

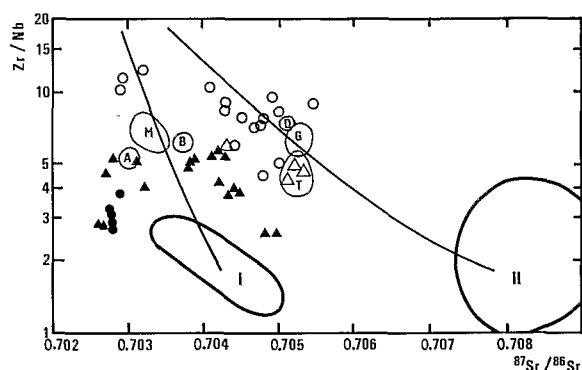


Fig. 5. Zr/Nb vs.  $^{87}\text{Sr}/^{86}\text{Sr}$  for Marquesas (open symbols) and Austral-Cook (solid symbols) Islands. Data from Duncan et al. (1986) (open triangles); Dupuy et al. (1987) (open circles); Vidal et al. (1984) (solid circles); Palacz and Saunders (1986) (solid triangles). Fields for kimberlites I and II and South Atlantic islands (M=Marion; A=Ascension; B=Bouvet; G=Gough Islands; T=Tristan da Cunha Island; D=Discovery Seamount) from Le Roex (1986).

distinct geochemical signatures including separation into two groups as shown in trace-element and isotopic data are also found in OIB from the South Atlantic and in kimberlites (Le Roex, 1986) and from isotopic data of carbonates (Nelson et al., 1988) and lamproites (Fraser et al., 1985).

## 5. Interpretation

The origin of the AC basalts (Dupuy et al., 1988) has been recently related to an ancient subducted and recycled lithosphere because: (a) the chondrite-normalized ITE pattern of these basalts are complementary to those of IAT; and (b) the isotopic data indicate the presence of a HIMU component which is considered to be the result of the incorporation of ancient oceanic crust from which the alteration component has been removed by subduction-related processes (Zindler and Hart, 1986).

The ITE ratios which discriminate between the two groups of island chains are those which are fractionated by subduction-related processes. These ratios such as high Ba/La ( $> 25$ ), low Pb/Ce ( $< 4$ ) and low Nb/La ( $< 0.4$ ) are characteristic of IAB (Kay, 1980; Morris and Hart, 1983; Ewart and Hawkesworth, 1987). Assuming that the values of these ratios in IAB are related to the amount of the melt extracted from the subducted lithosphere, the respective position of both groups and IAB in Fig. 3 would indicate that the mantle source for MA and SO basalts has been affected by the extraction of a smaller amount of the IAB component during subduction than that for AC basalts.

The mantle source of MA and SO basalts exhibits a chondritic value for many ITE ratios, probably including Nb/U. The latter ratio is strongly scattered because of the mobility of U during alteration, as is shown for instance in sample MAP which is relatively enriched in U (Table I). This sample MAP which was dredged from Moua Pihaa Seamount, has Nb/U = 5 and LOI  $> 5\%$  and has been affected by seawater al-

teration. On the other hand, some samples collected inland are depleted in U, resulting in high Nb/U ( $> 60$ ), and have meteoric alteration. In spite of these secondary effects, Table II suggests that Nb/U is lower in MA and SO basalts than in AC basalts; the latter have Nb/U ratios similar to those reported by Hofmann et al. (1986) for OIB and MORB. Among MA and SO basalts exhibiting a flat pattern in Fig. 2, Nb/U ranges from 37 to 48. Like Ba, U is fractionated relative to Nb, with the corresponding ratios Nb/U and Ba/Nb evolving from typically chondritic values in SO basalts to respectively higher and lower values in AC basalts.

Although the chondritic values for ITE ratios suggest that the mantle source of MA and SO basalts resembles the primitive mantle, this alternative is inconsistent with the isotopic data. The MA basalts have higher  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios than the bulk silicate Earth (Dupuy et al., 1987). However, the chondritic ITE ratios may be produced by mixing of two end-members, where the first end-member corresponds to the subducted harzburgitic layer while the second represents the overlying oceanic crust which was altered and/or contained sediments. The mixing of these two end-members may explain the range of Nd and Sr isotopic variations in the MA basalts. From Fig. 4 it is suggested that, as a first approximation, the basalts plot along a line connecting the harzburgite layer (component 1) and altered oceanic crust (component 2). The isotopic ratios of these two components have been estimated assuming that the ancient subduction zone is 1 Ga old and contains harzburgites and altered crust. In this figure, the underlying harzburgite has the following isotopic composition:  $^{143}\text{Nd}/^{144}\text{Nd}=0.51308$  and  $^{87}\text{Sr}/^{86}\text{Sr}=0.7023$ . The isotopic composition of the altered oceanic crust was calculated in the following manner: starting with the previous value for  $^{143}\text{Nd}/^{144}\text{Nd}$  and taking  $^{147}\text{Sm}/^{144}\text{Nd}=0.258$  in the underlying harzburgite, a value given by Allègre et al. (1983), the calculated  $^{143}\text{Nd}/^{144}\text{Nd}$  at 1 Ga is 0.511387. This value was used to calculate the present-day  $^{143}\text{Nd}/$

$^{144}\text{Nd}$  for the oceanic crust assuming  $^{147}\text{Sm}/^{144}\text{Nd}=0.20$  (dolerites and pillow lavas from the 400-Ma-old Bay of Islands ophiolite complex (Newfoundland, Canada; Jacobsen and Wasserburg, 1979). The  $^{87}\text{Sr}/^{86}\text{Sr}$  has been taken arbitrarily as 0.706 assuming that this ratio has been increased due to interaction with seawater (prior to subduction) and the alteration process does not significantly change the  $^{143}\text{Nd}/^{144}\text{Nd}$  ratio.

Likewise, the isotopic ratios of AC basalts can be explained by mixing of the same harzburgitic end-member with a crustal end-member containing low  $^{87}\text{Sr}/^{86}\text{Sr}$  compared to the MA basalts. The low  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio resulted from the extraction of mobile elements from the ancient oceanic crust component during subduction (Dupuy et al., 1988). Such an extraction would have lowered Rb/Sr and consequently limited the increase of  $^{87}\text{Sr}/^{86}\text{Sr}$  with time. In extreme cases of extraction of an IAB component by dehydration and partial melting, the oceanic crust may have lost all its fertile components. According to partition coefficient values, this extraction may lead to a depletion of Rb relative to Sr but cause only a small change in Sm/Nd. Finally, basalts with typical HIMU features are generated by the mixing of the harzburgitic component and a residual oceanic crust as suggested by Zindler and Hart (1986). In Fig. 4 such residual crust is labeled "3". Its isotopic composition was calculated assuming a low  $^{87}\text{Rb}/^{86}\text{Sr}$  of  $\sim 0.003$  corresponding to its refractory nature.  $^{143}\text{Nd}/^{144}\text{Nd}$  was calculated in a similar manner assuming  $^{147}\text{Sm}/^{144}\text{Nd}=0.21$ . The slight increase of this ratio, compared to that used for altered crust, resulted again from the more refractory character of this end-member. The basalts which exhibit such HIMU characteristics are more abundant in the AC Islands (Tubuai, Mangaia, Rurutu) but sporadically appear elsewhere in Polynesia (e.g., tholeiites from Ua Pou of the MA Islands). Their presence is probably ubiquitous but their volumes remain relatively small.

An alternative model for the Polynesian ba-

salts involves mixing between depleted MORB mantle and a highly enriched mantle component such as kimberlites (Le Roex, 1986) or carbonatites (Nelson et al., 1988). The two geochemically distinct groups of Polynesian basalts would require two enriched end-members with different compositions. These end-members may be represented by group-I and -II kimberlites (Smith, 1983; Smith et al., 1985) which have the same distinct geochemical signatures as the MA and AC basalts, respectively. Group-II kimberlites with higher  $^{87}\text{Sr}/^{86}\text{Sr}$  but lower  $^{206}\text{Pb}/^{204}\text{Pb}$  (Le Roex, 1986) may be the enriched end-member for MA and SO basalts whereas group-I kimberlites with lower  $^{87}\text{Sr}/^{86}\text{Sr}$  but higher  $^{206}\text{Pb}/^{204}\text{Pb}$  (Le Roex, 1986) are a potential enriched end-member for AC basalts (Fig. 5). A similar hypothesis of mixing involving enriched end-members with kimberlitic composition was invoked by Le Roex (1986) for basalts from the South Atlantic. He postulated that the two types of kimberlites have their source regions within the asthenosphere with group-II kimberlites derived from recycled lithospheric material.

The separation into two geochemically distinct groups which is also found in a large variety of volcanic rocks such as alkali basalts, kimberlites and lamproites suggests either two distinct asthenospheric sources or a single recycled lithospheric source which was affected by subduction processes to variable extents.

## 6. Conclusions

From the preceding discussion the choice between the two alternative models is not obvious. However, if the subduction processes are the only mechanisms which fractionate the ITE ratios (e.g., Weaver et al., 1986), then it may be postulated that the recycled lithosphere was the source of most of the undersaturated rocks. When applied to the Polynesian basalts, this model, which has been suggested by Hofmann and White (1982), provides an explanation for the isotopic Sr-Nd data as well as the large

variation of ratios involving the most incompatible trace elements. The mantle heterogeneities in southern Polynesia may be explained by mixing processes between two components of the recycled lithosphere (oceanic crust and underlying harzburgitic layer) with one of these components (oceanic crust) being subjected to variable chemical changes during subduction.

## Acknowledgements

The study was supported by ATP-PIROCEAN No. 0693 (France), ORSTOM (Institut Français de Recherche Scientifique pour le Développement en Coopération, France), and the Natural and Engineering Research Council of Canada (operating grant A3782).

Thanks are due to A.W. Hofmann, W.F. McDonough and an anonymous reviewer for improving the manuscript.

## References

- Allègre, C.J., Hart, S.R. and Minster, J.F., 1983. The chemical structure of the mantle determined by inversion of isotopic data, II. Numerical experiments and discussion. *Earth Planet. Sci. Lett.*, 66: 190-213.
- Bellon, H., 1974. Histoire géochronométrique des îles Gambier. *Cah. Pac.*, 1: 245-252.
- Calmant, S. and Cazenave, A., 1986. The effective elastic lithosphere under the Cook-Austral and Society islands. *Earth Planet. Sci. Lett.*, 77: 187-202.
- Calmant, S. and Cazenave, A., 1987. Anomalous elastic thickness of the oceanic lithosphere in the South-Central Pacific. *Nature (London)*, 328: 236-238.
- Chauvel, C., Vidal, P. and Hofmann, A.W., 1986. Mantle heterogeneities beneath the Austral Islands. *Terra Cognita*, 6: 241 (abstract).
- CPCEMR (Circum-Pacific Council for Energy and Mineral Resources), 1981. Plate-tectonic map of the Circum-Pacific region, Southeast Quadrant. *Circ.-Pac. Counc. Energy Miner. Resour., Circ.-Pac. Map Proj.*, Menlo Park, Calif. (scale 1:100,000).
- Dalrymple, G.B., Jarrard, R.D. and Clague, D.A., 1975. K-Ar ages of some volcanic rocks from the Cook and Austral Islands. *Geol. Soc. Am. Bull.*, 86: 1463-1467.
- Dautria, J.-M., Dostal, J., Dupuy, C. and Liotard, J.-M., 1988. Geochemistry and petrogenesis of alkali basalts from Tahalra (Hoggar, Northwest Africa). *Chem. Geol.*, 69: 17-35.
- Dostal, J., Dupuy, C. and Liotard, J.-M., 1982. Geochem-



- istry and origin of basaltic lavas from Society Islands. *Bull. Volcanol.*, 45: 51-62.
- Dostal, J., Baragar, W.R.A. and Dupuy, C., 1986. Petrogenesis of the Natkusiak continental basalts, Victoria Island, Northwest Territories, Canada. *Can. J. Earth Sci.*, 23: 622-632.
- Duncan, R.A. and Compston, W., 1976. Sr-isotope evidence for an old mantle source region for French Polynesian volcanism. *Geology*, 4: 728-732.
- Duncan, R.A. and McDougall, I., 1976. Linear volcanism in French Polynesia. *J. Volcanol. Geotherm. Res.*, 1: 197-227.
- Duncan, R.A., McCulloch, M.T., Barszczus, H.G. and Nelson, D.R., 1986. Plume versus lithospheric sources for melts at Ua Pou, Marquesas Islands. *Nature (London)*, 322: 534-538.
- Dupré, B., Hamelin, B. and Allègre, C.J., 1985. Large scale heterogeneity in mantle source of OIB and MORB. *Terra Cognita*, 5: 272 (abstract).
- Dupuy, C., Vidal, P., Barszczus, H.G. and Chauvel, C., 1987. Origin of basalts from the Marquesas Archipelago (south central Pacific Ocean): isotope and trace element constraints. *Earth Planet. Sci. Lett.*, 82: 145-152.
- Dupuy, C., Barszczus, H.G., Liotard, J.-M. and Dostal, J., 1988. Trace element evidence for the origin of ocean island basalts: an example from the Austral Islands (French Polynesia). *Contrib. Mineral. Petrol.*, 98: 293-302.
- Ewart, A. and Hawkesworth, C.J., 1987. The Pleistocene-Recent Tonga-Kermadec Arc lavas: Interpretation of new isotopic and rare earth data in terms of a depleted mantle source model. *J. Petrol.*, 28: 295-530.
- Fraser, K.J., Hawkesworth, C.J., Erlank, A.J., Mitchell, R.A. and Scott-Smith, B.H., 1985. Sr, Nd, and Pb isotope and minor element geochemistry of lamproites and kimberlites. *Earth Planet. Sci. Lett.*, 76: 57-70.
- Green, D.H., 1971. Composition of basaltic magmas as indicator of conditions of origin: application to oceanic volcanism. *Philos. Trans. R. Soc. London, Ser. A*, 268: 707-725.
- Hart, S.R., 1988. Heterogeneous mantle domains: signatures, genesis and mixing chronologies. *Earth Planet. Sci. Lett.*, 90: 273-296.
- Haxby, W.F. and Weissel, J.K., 1986. Evidence for small-scale mantle convection from Seasat altimeter data. *J. Geophys. Res.*, 91: 3507-3520.
- Hofmann, A.W. and White, W.M., 1980. The role of subducted oceanic crust in mantle evolution. *Carnegie Inst. Washington, Yearb.*, 79: 477-483.
- Hofmann, A.W. and White, W.M., 1982. Mantle plumes from ancient oceanic crust. *Earth Planet. Sci. Lett.*, 57: 421-436.
- Hofmann, A.W., Jochum, K.P., Seufert, M. and White, W.M., 1986. Nb and Pb in oceanic basalts: new constraints on mantle evolution. *Earth Planet. Sci. Lett.*, 79: 33-45.
- Jacobsen, S.B. and Wasserburg, G.J., 1979. Nd and Sr isotopic study of the Bay of Islands ophiolite complex and the evolution of the source of Midocean Ridge Basalts. *J. Geophys. Res.*, 84: 7429-7444.
- Jagoutz, E., Palme, H., Baddenhausen, H., Blum, K., Cendales, M., Dreibus, G., Spettel, B., Lorenz, V. and Weanke, H., 1979. The abundances of major, minor and trace elements in the earth's mantle as derived from primitive ultramafic nodules. *Proc. Lunar Planet. Sci. Conf.*, 10: 2031-2050.
- Jochum, K.P., Seufert, H.M., Spettel, B. and Palme, H., 1986. The solar-system abundances of Nb, Ta, and Y, and the relative abundances of refractory lithophile elements in differentiated planetary bodies. *Geochim. Cosmochim. Acta*, 50: 1173-1183.
- Kato, T., Ringwood, A.E. and Irifune, T., 1988. Experimental determination of element partitioning between silicate perovskites, garnets and liquids: constraints on early differentiation of the mantle. *Earth Planet. Sci. Lett.*, 89: 123-145.
- Kay, R.W., 1980. Volcanic arc magmas: implications of a melting-mixing model for elements recycled in the crust-upper mantle system. *J. Geol.*, 88: 497-522.
- Le Roex, A.P., 1986. Geochemical correlation between southern African kimberlites and South Atlantic hot-spots. *Nature (London)*, 324: 243-245.
- Liotard, J.-M., Barszczus, H.G., Dupuy, C. and Dostal, J., 1986. Geochemistry and origin of basaltic lavas from Marquesas Archipelago, French Polynesia. *Contrib. Mineral. Petrol.*, 92: 260-268.
- Matsuda, J.I., Notsu, K., Okano, J., Yaskawa, K. and Chungue, L., 1984. Geochemical implications from Sr isotopes and K-Ar age determinations for the Cook-Austral Islands chain. *Tectonophysics*, 104: 145-154.
- McCulloch, M.T., Jacques, A.L., Nelson, D.R. and Lewis, J.D., 1983. Nd and Sr isotopes in kimberlites and lamproites from Western Australia: an enriched mantle origin. *Nature (London)*, 302: 400-403.
- McDougall, I. and Duncan, R.A., 1980. Linear volcanic chains - recording plate motions? *Tectonophysics*, 63: 275-295.
- McNutt, M.K. and Fischer, K.M., 1987. The South Pacific Superswell. In: B.H. Keating, P. Fryer, R. Batiza and G.W. Boehlert (Editors), *Seamounts, Islands, and Atolls*. Am. Geophys. Union, *Geophys. Monogr.*, 43: 25-34.
- Morris, J.D. and Hart, S.R., 1983. Isotopic and incompatible element constraints on the genesis of island arc volcanics from Cold Bay and Amak Island, Aleutians, and implications for mantle structure. *Geochim. Cosmochim. Acta*, 47: 2015-2030.
- Nelson, D.R., Chivas, A.R., Chappell, B.W. and McCulloch, M.T., 1988. Geochemical and isotopic systematics in carbonatites and implications for the evolution of ocean-island sources. *Geochim. Cosmochim. Acta*, 53: 1-17.

- Nishimura, C.E. and Forsyth, D.W., 1985. Anomalous Love-wave phase velocities in the Pacific: sequential pure-path and spherical harmonic inversion. *Geophys. J. R. Astron. Soc.*, 81: 389-407.
- Norris, R.A. and Johnson, R.H., 1969. Submarine volcanic eruptions recently located in the Pacific by SOFAR hydrophones. *J. Geophys. Res.*, 74: 650-654.
- Palacz, Z.A. and Saunders, A.D., 1986. Coupled trace element and isotope enrichment in the Cook-Austral-Samoa Islands, southwest Pacific. *Earth Planet. Sci. Lett.*, 79: 270-280.
- Ringwood, A.E., 1982. Phase transformations and differentiation in subducted lithosphere: implications for mantle dynamics, basalts petrogenesis, and crustal evolution. *J. Geol.*, 90: 611-643.
- Ringwood, A.E., 1986. Dynamics of subducted lithosphere and implications for basalt petrogenesis. *Terra Cognita*, 6: 67-77 (abstract).
- Rocaboy, A., Vidal, P. and Dupuy, C., 1988. Composition du manteau: le réservoir HIMU. *Int. Congr. Geochem. Cosmochem.*, Paris, Aug. 29-Sept. 2, 1988. *Chem. Geol.*, 70: 56 (abstract).
- Ryerson, F.J. and Watson, E.B., 1987. Rutile saturation in magmas: implications for Ti-Nb-Ta depletion in island-arc basalts. *Earth Planet. Sci. Lett.*, 86: 225-239.
- Smith, C.B., 1983. Pb, Sr and Nd isotopic evidence for sources of southern African Cretaceous Kimberlites. *Nature (London)*, 304: 51-54.
- Smith, C.B., Gurney, J.J., Skinner, E.M.W., Clement, C.R. and Ebrahim, N., 1985. Geochemical character of southern African kimberlites: a new approach based on isotopic constraints. *Trans. Geol. Soc. S. Afr.*, 88: 267-280.
- Sun, S.S., 1982. Chemical composition and origin of the earth's primitive mantle. *Geochim. Cosmochim. Acta*, 46: 179-192.
- Sun, S.S. and McDonough, W.F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: A.D. Saunders and M.J. Norry (Editors), *Magmatism in Ocean Basins*. Shiva, Nantwich (in press).
- Sun, S.S., Nesbitt, R.W. and Sharaskin, A.Y., 1979. Geochemical characteristics of mid-ocean ridge basalts. *Earth Planet. Sci. Lett.*, 44: 119-138.
- Talandier, J. and Okal, E.A., 1984. The volcanoseismic swarms of 1981-1983 in the Tahiti-Mehetia area, French Polynesia. *J. Geophys. Res.*, 89B: 11216-11234.
- Tatsumoto, M., Unruh, D.M., Pettingill, H.S., Basu, A.R. and Barszczus, H.G., 1983. Pb, Nd, and Sr isotopes in volcanic rocks from Tubuai Islands. *Eos (Trans. Am. Geophys. Union)*, 64: 348 (abstract).
- Taylor, S.R., 1980. Refractory and moderately volatile element abundances in the earth, moon and meteorites. *Proc. Lunar Planet. Sci. Conf.*, 11: 333-348.
- Taylor, S.R. and McLennan, S.M., 1985. *The Continental Crust: Its Composition and Evolution*. Blackwell, Oxford, 312 pp.
- Turner, D.L. and Jarrard, R.D., 1982. K-Ar dating of the Cook-Austral island chain: a test of the hot spot hypothesis. *J. Volcanol. Geotherm. Res.*, 12: 187-220.
- Vidal, P., Chauvel, C. and Brousse, R., 1984. Large mantle heterogeneity beneath French Polynesia. *Nature (London)*, 307: 536-538.
- Vidal, P., Dupuy, C., Barszczus, H.G. and Chauvel, C., 1987. Hétérogénéités du manteau et origine des basaltes des Marquises (Polynésie). *Bull. Soc. Géol. Fr.*, 8e Sér., 3: 633-642.
- Weaver, B.L., Wood, D.A., Tarney, J. and Joron, J.L., 1986. Role of subducted sediments in the genesis of oceanic island basalts: Geochemical evidence from South Atlantic Ocean Islands. *Geology*, 14: 275-278.
- White, W.M., Dupré, B. and Vidal, P., 1985. Isotope and trace element geochemistry of sediments from the Barbados Ridge-Demerara Plain region, Atlantic Ocean. *Geochim. Cosmochim. Acta*, 49: 1875-1886.
- Wood, D.A., Tarney, J., Varet, J., Saunders, A.D., Bougault, H., Joron, J.L., Treuil, M. and Cann, J.R., 1979a. Geochemistry of basalts drilled in the North Atlantic by IPOD Leg 49: Implications for mantle heterogeneity. *Earth Planet. Sci. Lett.*, 42: 77-97.
- Wood, D.A., Joron, J.-L., Treuil, M., Norry, M. and Tarney, J., 1979b. Elemental and Sr isotope variations in basic lavas from Iceland and the surrounding ocean floor. *Contrib. Mineral. Petrol.*, 70: 319-339.
- Zindler, A. and Hart, S., 1986. Chemical geodynamics. *Annu. Rev. Earth Planet. Sci.*, 14: 493-571.
- Zindler, A., Jagoutz, E. and Goldstein, S., 1982. Nd, Sr and Pb isotopic systematics in a three-component mantle: a new perspective. *Nature (London)*, 298: 519-523.
- Zindler, A., Staudigel, H. and Batiza, R., 1984. Isotope and trace element geochemistry of young Pacific seamounts: implications for the scale of upper mantle heterogeneity. *Earth Planet. Sci. Lett.*, 70: 175-195.