

## Origin of the Jurassic Tethyan Ophiolites in Bosnia: A Geochemical Approach to Tectonic Setting

Fabijan TRUBELJA<sup>1</sup>, Vesna MARCHIG<sup>2</sup>, Klaus Peter BURGATH<sup>2</sup> & Željko VUJOVIĆ<sup>3</sup>

**Key words:** Tethys ophiolite, Oceanic spreading, Fracture zone, Amphibolites, Trace elements, Rare earth elements

### Abstract

The ophiolites from Bosnia are products of the Jurassic spreading of the Neo-Tethys, and are fragments of a long chain of ophiolites of the same origin. Their geological characteristics are the absence of a sheeted dyke complex and the tectonic disruption of the cumulate sequence. Upper crust volcanics as well as lower crust cumulates show low metamorphic changes of the prehnite/laumontite type, except for some marginal localities of large ophiolite massifs (Višegrad, Konjuh, Krivaja, Ozren) in which the metamorphic grade reaches the amphibolite facies.

The characteristic features of these ophiolites are as follows:

The mantle rocks are lherzolites and harzburgites, both characterized by a negative Eu-anomaly and a few of them have a negative Ce anomaly, which is explained as alteration due to contact with sea water.

The cumulate rocks are gabbroic to ultramafic. Numerous amphibolites reveal a chemical character of cumulus rocks. Early crystallization of plagioclase in the magma chamber caused positive Eu anomalies in these rocks. The upper crust rocks are basalts, diabases and gabbros. Most of them reveal REE patterns which are typical for basalts from constructive plate margins. A few of them which have a slight enrichment of LREE are explained as the partial melt products of a mantle less depleted than the one which produced the majority of basalts.

Chemical discrimination diagrams show that the magmatic rocks are of the mid-oceanic ridge type, i.e. that they formed at the spreading of oceanic plates without any influence from a subducted slab. A comparison with recent spreading zones shows that ophiolites of the described type (absence of a sheeted dyke complex, areas of tectonic disruption in the upper and lower crust, local amphibolitisation and eruptions of "enriched" MORB) probably have formed in areas of the intersection of spreading and a transform fault.

In most of their characteristics the ophiolites from Bosnia show a close similarity to the Ligurian ophiolites which obducted in about the same period of time and which are also products of the spreading of Neo-Tethys.

### 1. INTRODUCTION

The opening of Neo-Tethys during the Late Jurassic resulted from the break-off of several microplates from the Gondwana continent (Anatolia, Central Iran, Afghanistan, Central Tibet) and their drifting in a northerly direction (DEWEY et al., 1973; STONELEY, 1974; BOULIN, 1981). The first volcanic activity was triggered by rifting of continental crust and it produced a wide range of lava types, from alcalic to tholeiitic (TERRY, 1971; HYNES, 1974; ROBERTSON & WOODCOCK, 1979, 1981; CORTESOGNO & GAGGERO, 1992; CORTESOGNO et al., 1992).

The next magmatic stage was caused by spreading of young oceanic crust which is actually represented by several ophiolite belts. These ophiolite belts stretch from the western Alps and the Apennines (including Corsica) over the eastern and western ophiolite belts of the Balkan Peninsula to the ophiolites in Turkey, Syria and Oman. They become younger and change their chemical characteristics from North to South (BICKLE & PEARCE, 1975; FERRARA et al., 1976; BECCALUVA et al., 1977; CAPREDI et al., 1980; NOIRET et al., 1981; BECCALUVA et al., 1984).

The ophiolites from Bosnia investigated in this study (Fig. 1, Table 1) belong to the western belt of ophiolites on the Balkan Peninsula. They are fragments of a long chain of ophiolites of the same origin, which are part of zone IVb of the Dinarides after KOSSMAT (1924). The prolongation of this western belt passes through western Serbia (Zlatibor ophiolite) over Kosovo and the western belt of the Mirdita ophiolite in Albania to the Pindos and Othris ophiolites in central Greece.

### 2. GEOLOGICAL SETTING AND PREVIOUS INVESTIGATIONS

In Bosnia and Herzegovina the ophiolite unit together with associated sediments covers a surface of several tens of thousands of square kilometers. Two large mountain ranges, Krivaja-Konjuh and Ozren, are exclusive-

<sup>1</sup> Geotehnički fakultet, Hallerova 7, 42000 Varaždin, Croatia.

<sup>2</sup> Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany.

<sup>3</sup> Department of Earth Sciences, The Open University, Milton Keynes, England.

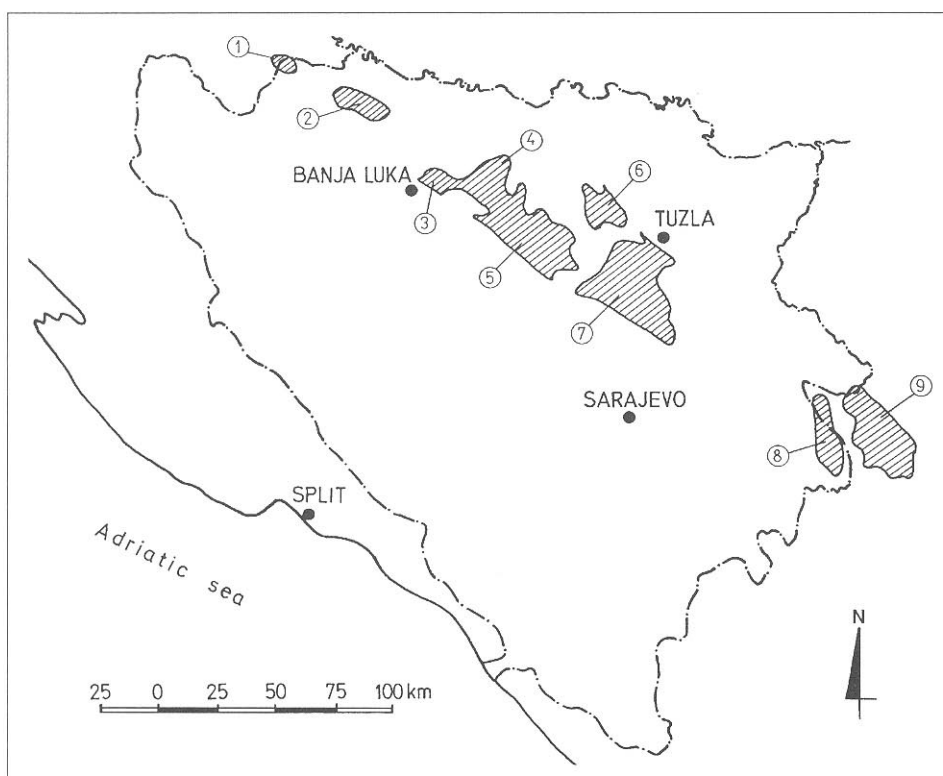


Fig. 1 Distribution of ophiolite complexes in the central part of the Dinarides in the region of Bosnia and Herzegovina. Legend: 1) Pastirevo; 2) Kozara; 3) Skatovica; 4) Čavka; 5) Borja; 6) Ozren; 7) Krivaja-Konjuh; 8) Varda; 9) Zlatibor.

ly built up of ophiolitic material. Several hillocks, such as Borja, Mahnjača, Ljubić, and Čavka, situated between the Bosna and Vrbas rivers, also consist of ophiolite sequences. The large mountain massive of Kozara in the northern part of Bosnia also consists to a large extent of ophiolitic rocks. The ophiolite material occurring in the vicinity of Višegrad is the western foothill of the Zlatibor ophiolite complex; adjacent to it the ophiolitic Varda complex is situated. The sketch map in Fig. 1 shows the distribution of Jurassic ophiolites in Bosnia. All the occurrences are dismembered ophiolite sequences, but all segments of a typical ophiolite are present: ultramafic mantle tectonites, ultramafic to mafic cumulates, gabbros, diabases and basaltic rocks. A thick layer of marine sediments on the top of the ophiolite complex is of Jurassic age, and is largely composed of continental shelf and slope sediments with a lesser proportion representing deep sea environment. The sediments are partly interlayered with basaltic sequences on the top of the ophiolite; some basalts are present as sills in the sediments and some poured out as lava flows over the sediment surface. A typical development of a sheeted dyke complex could not be found within the Bosnian ophiolite suite. Instead, a tectonically strongly disrupted area was observed in which gabbros and diabases occur. Ophiolites without a sheeted dyke complex have also been described from Alpine and Apennine areas, the Caucasus and Papua New Guinea; they are interpreted as the products of spreading of young and thin oceanic crust, possibly formed in a fracture zone setting (BARRET & SPOONER, 1977).

The magmatic rocks are usually slightly metamorphosed (zeolite to greenschist facies), but locally the

metamorphic grade reaches amphibolite facies. The amphibolites are concentrated in the surroundings of Vareš (exposures near Vijaka village and in the Krivaja river valley). Two different types of amphibolites were sampled; metamorphosed cumulate rocks and metamorphosed basalts and diabases (e.g. at Ribnica, Krivaja river valley).

K/Ar dating of amphibolites which originated from cumulate rocks gave a range between 160 and 170 m.y. (LANPHERE et al., 1975). This Middle Jurassic age is interpreted as the age of tectonic emplacement of the ophiolite. In the ophiolites of the Northern Apennines with very similar structures to the Bosnian ophiolites, fission track investigation of fresh cumulates also yielded Middle Jurassic ages (BIGAZZI et al., 1973). This indicates a short time interval between spreading and the final tectonic emplacement of the protoliths of the ophiolites in Bosnia and Herzegovina.

The ophiolite zone in Bosnia has a research history of more than a century. KIŠPATIĆ (1897 and 1900) described the mantle rocks as the "Bosnian serpentine zone" and, based on their high metamorphic grade, considered them to be of Archaean age.

More recently several publications have dealt with this area. Those relevant to the present study include: TRUBELJA, 1960, 1961; MAJER, 1962; TRUBELJA & PAMIĆ, 1965; TRUBELJA et al., 1978; MAJER et al., 1979; PAMIĆ, 1971, 1974, 1982a, b; PAMIĆ & DESMONS, 1989; PAMIĆ et al., 1973; LUGOVIĆ et al., 1991. The best overview of the distribution of the rock types, their occurrences, and their relationship to the associated sediments is presented in the new geological map of Bosnia and Herzegovina. The recently

| Mantle rocks          |  |  |   |
|-----------------------|--|--|---|
| O-1                   | harzburgite, Višegrad                        | V-25   | amphibolite, region Vijaka-Krivaja-Duboštica  |
| 0-1A                  | harzburgite, Višegrad                        | V-26   | amphibolite, region Vijaka-Krivaja-Duboštica  |
| 0-3B                  | harzburgite, Višegrad                        | V-27   | amphibolite, region Vijaka-Krivaja-Duboštica  |
| 0-7                   | harzburgite, Konjuh                          | V-27A  | amphibolite, region Vijaka-Krivaja-Duboštica  |
| V-1E                  | harzburgite, region Konjuh - Krivaja         | <b>Upper part of ophiolite sequence - normal (La/LuCN &lt;1)</b>   |   |
| V-2B/1                | harzburgite, region Konjuh - Krivaja         | 0-2B   | diabase, Višegrad                             |
| V-4A                  | lherzolite, region Konjuh - Krivaja          | 0-4  | dolerite, Višegrad                            |
| V-16A/P               | lherzolite, Duboštica                        | 0-6  | diabase, Višegrad                             |
| V-22                  | lherzolite, Duboštica                        | 0-8  | diabase, Konjuh                               |
| <b>Cumulate rocks</b> |  | 0-10   | spilite, Konjuh                               |
| 0-2                   | olivine gabbro, Višegrad                     | 0-11   | diabase, Konjuh                               |
| 0-2A                  | anortosite, Višegrad                         | 0-13   | diabase, Konjuh                               |
| 0-3                   | troctolite, Višegrad                         | 0-15   | basalt, Višegradska Banja                     |
| 0-14                  | olivine gabbro, Konjuh                       | 0-16   | amphibolite, Ribnica (Konjuh)                 |
| 0-23A                 | peridotite, Duboštica                        | 0-18   | diabase, Ribnica (Konjuh)                     |
| 0-24                  | amphibolite, Duboštica                       | 0-21   | spilite, Ribnica (Konjuh)                     |
| 0-27                  | amphibole-coisite schist, Boljanić, Ozren    | 0-22   | spilite, Ribnica (Konjuh)                     |
| 0-28                  | corundum amphibolite, Donja Vijaka (Vareš)   | 0-24A  | garnet amphibolite, Duboštica                 |
| 0-34                  | amphibolite, region Vijaka-Krivaja-Duboštica | 0-31   | amphibolite, region Ribnica-Krivaja-Duboštica |
| 0-36                  | amphibolite, region Vijaka-Krivaja-Duboštica | 0-38   | amphibolite, region Ribnica-Krivaja-Duboštica |
| 0-37                  | amphibolite, region Vijaka-Krivaja-Duboštica | V-8  | amphibolite, region Ribnica-Krivaja-Duboštica |
| 0-40                  | troctolite, Duboštica                        | V-12   | amphibolite, region Ribnica-Krivaja-Duboštica |
| 0-41                  | gabbro-peridotite, Duboštica                 | V-14   | amphibolite, region Ribnica-Krivaja-Duboštica |
| V-2A/K                | amphibolite, region Vijaka-Krivaja-Duboštica | V-16   | amphibolite, region Ribnica-Krivaja-Duboštica |
| V-2A/S                | amphibolite, region Vijaka-Krivaja-Duboštica | V-17   | amphibolite, region Ribnica-Krivaja-Duboštica |
| V-2B/3                | amphibolite, region Vijaka-Krivaja-Duboštica | V-18   | amphibolite, region Ribnica-Krivaja-Duboštica |
| V-2B/4                | amphibolite, region Vijaka-Krivaja-Duboštica | V-20   | spilite, region Ribnica-Krivaja-Duboštica     |
| V-2C                  | amphibolite, region Vijaka-Krivaja-Duboštica | V-24   | amphibolite, region Ribnica-Krivaja-Duboštica |
| V-4                   | amphibolite, region Vijaka-Krivaja-Duboštica | <b>Upper part of ophiolite sequence - enriched (La/LuCN &gt;1)</b> |   |
| V-5                   | amphibolite, region Vijaka-Krivaja-Duboštica | 0-16A  | diabase, Ribnica                              |
| V-5A                  | amphibolite, region Vijaka-Krivaja-Duboštica | 0-17   | diabase, Ribnica                              |
| V-6                   | amphibolite, region Vijaka-Krivaja-Duboštica | 0-20   | spilite, Ribnica                              |
| V-7                   | amphibolite, region Vijaka-Krivaja-Duboštica | 0-25   | spilite, Tribija                              |
| V-9                   | amphibolite, region Vijaka-Krivaja-Duboštica | 0-26   | diabase, Ozren                                |
| V-10                  | amphibolite, region Vijaka-Krivaja-Duboštica | V-7A   | amphibolite, region Krivaja-Duboštica         |
| V-11                  | amphibolite, region Vijaka-Krivaja-Duboštica | V-7A/1   | amphibolite, region Krivaja-Duboštica         |
| V-11A                 | amphibolite, region Vijaka-Krivaja-Duboštica | V-13   | amphibolite, region Krivaja-Duboštica         |
| V-15                  | amphibolite, region Vijaka-Krivaja-Duboštica | V-19   | amphibolite, region Krivaja-Duboštica         |
| V-23                  | amphibolite, region Vijaka-Krivaja-Duboštica | V-28   | amphibolite, region Krivaja-Duboštica         |

Table 1 Rock names and localities.

used term “diabase-chert formation” for this complex is certainly inadequate with respect to the very different rock members within this group.

### 3. METHODS OF INVESTIGATION

The material for this investigation was sampled during the summer seasons of 1990 and 1991. Thin sections were studied at the University of Sarajevo and chemical analyses were performed in the Federal Institute for Geosciences and Natural Resources (BGR) in Hannover. The following analytical methods were used:

- X-ray fluorescence spectroscopy (Philips PW 1400 spectrometer with Rh-source for trace elements and Philips PW 1480 spectrometer for major components). Both analyses were performed for the same sample + lithium metaborate glass (ratio 1:5) after ignition of the powdered sample at 1000° C.

- Inductively coupled plasma mass spectrometry (ICP-MS) for the determination of Sc, Y, and rare earth elements. Additionally the elements As, Hf, Mo, Sb, Sn, Ta, Th, U, and W were determined in 18 samples.

Unfortunately, the thin sections had to remain at the university of Sarajevo and were not available for further study and comparison with the chemical results.

Results of chemical analyses of investigated rocks are compiled in Table 2.

### 4. MANTLE SECTION; MINERALOGY AND PETROLOGY

The most widespread rocks in the investigated ophiolite complex are more or less serpentinized peridotites which belong to the upper mantle section. They are mostly lherzolites, but some occurrences also display harzburgite. Dunite was not found. Due to tectonic pro-



| Sample                         | V 2B/3 | V 2B/4 | V 2C  | V 4   | V 5   | V 5A  | V 6   | V 7   | V 9   | V 10  | V 11  | V 11A | V 15  | V 23  | V 25  | V 26  | V 27  | V 27A | O 2B  | O 4   | O 6   | O 8   | O 10  | O 11  |
|--------------------------------|--------|--------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| SiO <sub>2</sub>               | 46.61  | 45.90  | 48.86 | 48.77 | 48.48 | 48.39 | 46.80 | 50.08 | 44.91 | 46.10 | 48.74 | 47.70 | 49.65 | 46.73 | 46.90 | 47.75 | 48.86 | 49.67 | 49.26 | 49.22 | 49.98 | 48.71 | 49.69 | 49.82 |
| TiO <sub>2</sub>               | 0.07   | 0.12   | 0.10  | 0.59  | 0.19  | 0.22  | 0.18  | 0.33  | 0.10  | 0.22  | 0.22  | 0.17  | 0.37  | 0.16  | 0.14  | 0.24  | 0.13  | 0.09  | 2.21  | 0.62  | 1.32  | 2.86  | 1.51  | 1.82  |
| Al <sub>2</sub> O <sub>3</sub> | 15.78  | 20.18  | 19.34 | 14.59 | 17.20 | 17.17 | 24.29 | 16.92 | 27.96 | 19.50 | 18.51 | 22.15 | 15.49 | 21.25 | 18.61 | 20.95 | 17.21 | 20.07 | 14.24 | 15.43 | 15.00 | 13.73 | 14.10 | 14.08 |
| Fe <sub>2</sub> O <sub>3</sub> | 4.53   | 3.50   | 4.19  | 9.93  | 5.42  | 4.73  | 3.83  | 6.48  | 2.90  | 4.19  | 5.96  | 4.24  | 8.30  | 4.20  | 4.74  | 4.95  | 5.05  | 3.89  | 12.00 | 6.89  | 10.05 | 13.85 | 11.56 | 11.36 |
| MnO                            | 0.07   | 0.06   | 0.08  | 0.17  | 0.10  | 0.10  | 0.06  | 0.13  | 0.04  | 0.05  | 0.12  | 0.08  | 0.15  | 0.06  | 0.07  | 0.09  | 0.09  | 0.07  | 0.21  | 0.14  | 0.17  | 0.24  | 0.20  | 0.16  |
| MgO                            | 15.99  | 7.96   | 10.45 | 10.25 | 11.70 | 10.55 | 8.24  | 10.53 | 7.05  | 12.77 | 10.08 | 7.93  | 11.79 | 13.12 | 12.22 | 11.01 | 12.54 | 10.23 | 6.86  | 10.01 | 8.51  | 6.07  | 8.17  | 7.41  |
| CaO                            | 15.47  | 21.60  | 14.56 | 13.45 | 14.66 | 16.46 | 13.91 | 12.98 | 15.14 | 14.98 | 14.10 | 15.95 | 11.92 | 12.22 | 15.18 | 12.66 | 14.27 | 13.58 | 10.59 | 14.32 | 11.29 | 9.36  | 8.91  | 9.73  |
| Na <sub>2</sub> O              | 0.74   | 0.38   | 1.40  | 2.00  | 1.87  | 1.32  | 2.05  | 2.27  | 1.58  | 1.58  | 1.76  | 1.43  | 1.92  | 1.76  | 1.32  | 1.61  | 1.45  | 2.22  | 4.04  | 2.61  | 3.09  | 4.27  | 5.06  | 4.47  |
| K <sub>2</sub> O               | 0.04   | 0.00   | 0.65  | 0.03  | 0.11  | 0.65  | 0.06  | 0.09  | 0.03  | 0.05  | 0.26  | 0.07  | 0.15  | 0.07  | 0.36  | 0.54  | 0.03  | 0.05  | 0.08  | 0.05  | 0.11  | 0.08  | 0.24  | 0.32  |
| SO <sub>3</sub>                | 0.02   | 0.00   | 0.02  | 0.02  | 0.02  | 0.02  | 0.02  | 0.02  | 0.02  | 0.02  | 0.02  | 0.02  | 0.02  | 0.02  | 0.02  | 0.02  | 0.02  | 0.02  | 0.05  | 0.04  | 0.06  | 0.03  | 0.03  | 0.06  |
| *Ba                            | 24     | 12     | 72    | 14    | 15    | 53    | 22    | 91    | 17    | 12    | 29    | 15    | 19    | 12    | 27    | 291   | 20    | 21    | 1     | 1     | 1     | 1     | 1     | 1     |
| *Co                            | 41     | 14     | 37    | 47    | 31    | 33    | 36    | 38    | 15    | 33    | 31    | 19    | 43    | 31    | 36    | 36    | 40    | 32    | 21    | 1     | 1     | 24    | 1     | 21    |
| *Cr                            | 2697   | 824    | 578   | 281   | 1181  | 820   | 843   | 567   | 278   | 2144  | 595   | 530   | 364   | 1847  | 984   | 669   | 1482  | 747   | 131   | 669   | 221   | <100  | 316   | 122   |
| *Cu                            | 21     | 54     | 25    | 20    | 19    | 131   | 11    | 46    | 17    | 50    | 90    | 55    | 1     | 1     | 28    | 36    | 104   | 115   | 64    | 92    | 19    | 29    | 51    | 18    |
| *Ga                            | 8      | 7      | 8     | 12    | 9     | 15    | 11    | 12    | 8     | 8     | 9     | 13    | 13    | 7     | 9     | 11    | 9     | 12    | -     | -     | -     | -     | -     | -     |
| *Ni                            | 750    | 160    | 208   | 135   | 221   | 148   | 248   | 166   | 247   | 789   | 125   | 122   | 179   | 412   | 267   | 238   | 273   | 207   | 63    | 133   | 92    | 54    | 71    | 58    |
| *Se                            | 24     | 29     | 33    | 51    | 47    | 45    | 18    | 38    | 9     | 25    | 41    | 29    | 46    | 16    | 37    | 28    | 33    | 32    | 42    | 42    | 45    | 42    | 45    | 41    |
| *Sr                            | 29     | 7      | 148   | 82    | 309   | 140   | 127   | 142   | 99    | 60    | 253   | 122   | 101   | 61    | 99    | 152   | 149   | 154   | 141   | 118   | 148   | 180   | 136   | 177   |
| *V                             | 70     | 92     | 112   | 266   | 164   | 166   | 72    | 155   | 38    | 116   | 156   | 126   | 212   | 72    | 132   | 116   | 127   | 104   | 342   | 210   | 286   | 390   | 312   | 302   |
| *Y                             | 12     | 6      | 1     | 23    | 7     | 13    | 15    | 15    | 1     | 11    | 11    | 8     | 10    | 1     | 1     | 9     | 7     | 5     | 46    | 20    | 32    | 62    | 35    | 40    |
| *Zn                            | 41     | 15     | 21    | 77    | 30    | 26    | 27    | 46    | 19    | 9     | 30    | 20    | 52    | 15    | 15    | 27    | 21    | 58    | 72    | 43    | 38    | 50    | 77    | 19    |
| *Zr                            | 1      | 1      | 10    | 17    | 12    | 14    | 8     | 17    | 9     | 9     | 8     | 1     | 14    | 9     | 8     | 19    | 8     | 10    | 113   | <50   | 64    | 161   | 74    | 101   |
| La                             | 0.20   | 0.20   | 0.60  | 0.60  | 0.70  | 1.10  | 0.60  | 0.80  | 0.40  | 0.70  | 0.30  | 0.30  | 0.60  | 0.40  | 0.20  | 0.50  | 0.20  | 0.10  | 3.00  | 0.80  | 3.10  | 6.10  | 3.10  | 4.10  |
| Ce                             | 0.60   | 0.50   | 1.20  | 2.20  | 1.60  | 1.90  | 1.60  | 2.30  | 0.70  | 2.10  | 1.10  | 0.90  | 1.60  | 1.00  | 0.40  | 1.30  | 0.60  | 0.30  | 12.20 | 3.10  | 8.20  | 19.40 | 8.40  | 12.30 |
| Pr                             | 0.06   | 0.09   | 0.12  | 0.42  | 0.20  | 0.22  | 0.24  | 0.34  | 0.09  | 0.31  | 0.16  | 0.16  | 0.29  | 0.15  | 0.07  | 0.20  | 0.08  | 0.05  | 2.44  | 0.51  | 1.33  | 3.27  | 1.46  | 2.04  |
| Nd                             | 0.31   | 0.43   | 0.51  | 2.62  | 1.01  | 0.83  | 1.12  | 1.72  | 0.34  | 1.43  | 0.88  | 0.73  | 1.43  | 0.74  | 0.55  | 1.03  | 0.59  | 0.29  | 13.21 | 3.29  | 7.66  | 24.52 | 8.78  | 12.25 |
| Sm                             | 0.11   | 0.23   | 0.24  | 1.21  | 0.49  | 0.40  | 0.47  | 0.74  | 0.14  | 0.63  | 0.41  | 0.34  | 0.69  | 0.33  | 0.31  | 0.44  | 0.28  | 0.18  | 4.78  | 1.23  | 2.55  | 6.13  | 2.82  | 3.68  |
| Eu                             | 0.11   | 0.20   | 0.17  | 0.61  | 0.29  | 0.23  | 0.28  | 0.37  | 0.14  | 0.34  | 0.33  | 0.27  | 0.37  | 0.20  | 0.22  | 0.21  | 0.21  | 0.18  | 1.63  | 0.50  | 1.02  | 1.94  | 1.04  | 1.33  |
| Gd                             | 0.12   | 0.26   | 0.24  | 1.21  | 0.54  | 0.43  | 0.40  | 0.77  | 0.16  | 0.61  | 0.42  | 0.32  | 0.70  | 0.26  | 0.31  | 0.49  | 0.27  | 0.18  | 3.56  | 1.03  | 2.04  | 4.60  | 2.30  | 3.06  |
| Tb                             | 0.03   | 0.05   | 0.05  | 0.27  | 0.12  | 0.10  | 0.09  | 0.15  | 0.03  | 0.13  | 0.09  | 0.08  | 0.16  | 0.06  | 0.08  | 0.09  | 0.06  | 0.05  | 1.02  | 0.32  | 0.61  | 1.53  | 0.66  | 0.81  |
| Dy                             | 0.29   | 0.49   | 0.50  | 2.32  | 1.13  | 0.89  | 0.74  | 1.21  | 0.29  | 1.01  | 0.91  | 0.61  | 1.33  | 0.50  | 0.71  | 0.88  | 0.62  | 0.39  | 7.32  | 2.46  | 4.60  | 8.89  | 4.81  | 5.82  |
| Ho                             | 0.06   | 0.09   | 0.10  | 0.46  | 0.22  | 0.18  | 0.15  | 0.25  | 0.06  | 0.19  | 0.17  | 0.13  | 0.28  | 0.10  | 0.14  | 0.18  | 0.11  | 0.08  | 1.42  | 0.50  | 0.93  | 1.74  | 1.04  | 1.23  |
| Er                             | 0.15   | 0.30   | 0.28  | 1.41  | 0.65  | 0.58  | 0.43  | 0.75  | 0.21  | 0.57  | 0.49  | 0.39  | 0.80  | 0.29  | 0.40  | 0.52  | 0.31  | 0.23  | 4.47  | 1.44  | 2.86  | 5.31  | 3.24  | 3.57  |
| Tm                             | 0.02   | 0.04   | 0.04  | 0.22  | 0.10  | 0.09  | 0.07  | 0.11  | 0.03  | 0.08  | 0.08  | 0.06  | 0.12  | 0.05  | 0.06  | 0.08  | 0.05  | 0.03  | 0.63  | 0.03  | 0.45  | 0.80  | 0.44  | 0.51  |
| Yb                             | 0.20   | 0.30   | 0.29  | 1.72  | 0.72  | 0.56  | 0.48  | 0.83  | 0.27  | 0.59  | 0.61  | 0.42  | 0.92  | 0.34  | 0.42  | 0.60  | 0.34  | 0.25  | 4.17  | 1.54  | 2.76  | 5.31  | 3.24  | 3.37  |
| Lu                             | 0.03   | 0.04   | 0.05  | 0.25  | 0.10  | 0.10  | 0.07  | 0.12  | 0.03  | 0.08  | 0.09  | 0.07  | 0.14  | 0.05  | 0.07  | 0.09  | 0.05  | 0.03  | 0.61  | 0.24  | 0.45  | 0.78  | 0.52  | 0.56  |
| As                             | -      | -      | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | 3.56  | 3.29  | 3.17  | 3.37  | 3.87  | 4.19  |
| Hf                             | -      | -      | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | 3.56  | 0.82  | 3.98  | 1.43  | 2.93  | 1.94  |
| Mo                             | -      | -      | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | 0.59  | 0.47  | 0.68  | 0.29  | 0.55  | 0.66  |
| Nb                             | -      | -      | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | 2.6   | 0.71  | 6.13  | 1.72  | 2.31  | 2.65  |
| Sb                             | -      | -      | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | 0.23  | 0.11  | 0.24  | 0.14  | 0.16  | 0.19  |
| Sn                             | -      | -      | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | 1.83  | 0.62  | 1.74  | 0.92  | 1.15  | 1.12  |
| Ta                             | -      | -      | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | 0.76  | 0.32  | 0.48  | 0.26  | 0.26  | 0.26  |
| Th                             | -      | -      | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | 0.15  | <0.10 | 0.29  | <0.10 | 0.14  | 0.15  |
| U                              | -      | -      | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | 0.03  | 0.01  | 0.05  | 0.02  | 0.05  | 0.04  |
| W                              | -      | -      | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | -     | 0.21  | 0.75  | 0.42  | 0.09  | 0.19  | 0.15  |



| Sample                         | V 13  | V 19  | V 28  |
|--------------------------------|-------|-------|-------|
| SiO <sub>2</sub>               | 50.89 | 52.00 | 53.38 |
| TiO <sub>2</sub>               | 1.17  | 1.34  | 1.27  |
| Al <sub>2</sub> O <sub>3</sub> | 15.26 | 14.21 | 15.50 |
| Fe <sub>2</sub> O <sub>3</sub> | 10.31 | 11.34 | 9.33  |
| MnO                            | 0.17  | 0.20  | 0.16  |
| MgO                            | 8.06  | 7.35  | 7.39  |
| CaO                            | 10.16 | 9.43  | 8.79  |
| Na <sub>2</sub> O              | 3.32  | 3.69  | 3.35  |
| K <sub>2</sub> O               | 0.07  | 0.17  | 0.37  |
| SO <sub>3</sub>                | 0.02  | 0.02  | 0.02  |
| *Ba                            | 42    | 37    | 73    |
| *Co                            | 33    | 37    | 43    |
| *Cr                            | 233   | <100  | 349   |
| *Cu                            | 61    | 43    | 64    |
| *Ga                            | 14    | 11    | 14    |
| *Ni                            | 78    | 39    | 132   |
| *Sc                            | 42    | 44    | 38    |
| *Sr                            | 105   | 170   | 155   |
| *V                             | 287   | 299   | 267   |
| *Y                             | 21    | 36    | 31    |
| *Zn                            | 71    | 66    | 81    |
| *Zr                            | 63    | 84    | 86    |
| La                             | 5.00  | 5.30  | 6.20  |
| Ce                             | 12.80 | 13.60 | 16.20 |
| Pr                             | 1.73  | 1.85  | 2.07  |
| Nd                             | 7.51  | 8.00  | 8.74  |
| Sm                             | 2.54  | 2.84  | 2.98  |
| Eu                             | 0.99  | 1.00  | 0.85  |
| Gd                             | 2.54  | 2.63  | 2.88  |
| Tb                             | 0.48  | 0.52  | 0.52  |
| Dy                             | 3.86  | 4.05  | 4.01  |
| Ho                             | 0.75  | 0.82  | 0.73  |
| Er                             | 2.23  | 2.33  | 2.16  |
| Tm                             | 0.33  | 0.35  | 0.32  |
| Yb                             | 2.44  | 2.73  | 2.47  |
| Lu                             | 0.38  | 0.38  | 0.32  |
| As                             | -     | -     | -     |
| Hf                             | -     | -     | -     |
| Mo                             | -     | -     | -     |
| Nb                             | -     | -     | -     |
| Sb                             | -     | -     | -     |
| Sn                             | -     | -     | -     |
| Ta                             | -     | -     | -     |
| Th                             | -     | -     | -     |
| U                              | -     | -     | -     |
| W                              | -     | -     | -     |

Table 2 Bulk chemical composition of the investigated rocks. XRF, REE and ICP/MS are calculated free from 'loss of ignition'.

\* 1 ppm = under detection limit.

cesses some of the mantle peridotites are intermixed with rocks from the crustal ophiolite sequence.

The mantle peridotites reveal a monotonous mineral composition. The lherzolites are mainly composed of olivine, enstatite, diopside and spinel (spinel lherzolite type). In the harzburgite small amounts of clinopyroxene can be preserved, and frequently lamellae of clinopyroxene occur within the crystals of rhombic pyroxene. The olivine in the mantle peridotites is rich in magnesium (Fo about 90), and the same is valid for enstatite (En about 90).

The olivine is more or less replaced by serpentine minerals (mainly chrysotile and some lizardite). Antigorite was also observed as a replacement of olivine, but was not associated with chrysotile/ lizardite. Besides the minerals of the serpentine group, other secondary minerals were observed: chlorite, clinoamphibole, talc, magnetite and dolomite.

Gabbro pegmatites occur as veins and dykes in the mantle peridotite. These pegmatites contain large crystals of diopside (diplage) and plagioclase (bytownite, with transformation to labradorite and finally albite). They could represent the trapped parts of magma which furnished the magmatic sequence above the petrological Mohorovičić discontinuity (Moho).

## 5. ULTRAMAFIC-MAFIC CUMULATE SEQUENCE ABOVE THE PETROLOGIC MOHO; MINERALOGY AND PETROLOGY

Above the petrologic Moho, cumulate peridotites, a gabbro-peridotite transitional section and cumulate gabbros have been identified. All of them appear to be the products of differentiation in a crustal magma chamber. It is characteristic for the cumulate rocks that plagioclases occur very early in the cumulate crystallisation series (TRUBELJA, 1961).

Dunite and lherzolite represent the ultramafic cumulate rocks. The mineral composition of this lherzolite is the same as for the mantle lherzolite (olivine, enstatite, diopside). Also in the cumulate lherzolite olivine is transformed to serpentine-group minerals. Differences

between mantle lherzolite and cumulate lherzolite are best shown by the bulk chemical composition of the rocks.

Cumulate gabbros are widespread in the surrounding of Višegrad and are represented by troctolite, olivine gabbro and anorthosite (plagioclase-rich rocks) in rhythmic layering. TRUBELJA (1960) has described their petrography and the chemical characteristics. Cumulate gabbros usually show a hypidiomorphic to allotriomorphic texture. The main mineral components are calcic plagioclases (bytownite-anortite), clinopyroxene (diopside-diaplage), and olivine. The olivine grains are frequently rimmed by clinopyroxene. Alteration of olivine to serpentine is common. The serpentinisation of olivine always occurs parallel to the prehnitisation of plagioclase. In some of the cumulate gabbros, brown hornblende is a secondary reaction product, occurring as rims around diopside. Chlorite is rare and occurs as an alteration product of the ferromagnesian minerals. Magnetite is a frequent accessory mineral.

Deformational features, e.g. foliation, lineation, and the formation of porphyroclastic pyroxenes, are developed in the cumulate sequence. Deformational features, uncommon for the cumulate section of ophiolites, were also described by BURGATH & MOHR (1986) from the lower cumulate section of the MOR-type Bobaris ophiolite, Indonesia, and they were observed in active spreading zones in the setting of ridge-transform fault intersections (AUZENDE et al., 1994; BOUGAULT et al., 1993; FRANCHETEAU et al., 1990; HEKINIAN et al., in press). These intersections are characterised by very thin oceanic crust (RAITT, 1963; DETRICK & PURDY, 1980; FOX & GALLO, 1984; WHITE, 1984; WHITE et al., 1984) with the absence of a sheeted dyke complex (BARRET & SPOONER, 1977) and they are "tilted and wrench folded" and reveal a higher degree of metamorphism (AUZENDE et al., 1994). The ridge-transform fault intersection of the Mid Atlantic Ridge with the Kane Fracture Zone especially shows similarities with field observations in the Bosnian ophiolites, because their cumulate section is dissected by spectacular mylonitic zones.

## 6. UPPER MAGMATIC SEQUENCE (GABBROS, DIABASES AND BASALTS); MINERALOGY AND PETROLOGY

The upper magmatic sequence, situated above the cumulate niveau, is composed of intrusive gabbros and their volcanic equivalents (basalts). Strong tectonic disruption is characteristic for this sequence; in some places it is mixed with the deeper-seated cumulates and mantle peridotites. The most frequent forms occur as sills and dykes, although, as already mentioned, a sheeted dyke zone is not developed in these ophiolites. Deeper in the magmatic sequence gabbros with coarse-grained ophitic textures occur. The upper magmatic section is represented by diabases, dolerites, and basalts. The latter were later transformed to spilites. Frequently gabbros penetrated the diabases and dolerites and formed small separate dykes within the volcanic series. Fresh exposures of all these rocks of the upper magmatic section can be observed along the Olovo-Kladanj highway, which cuts through the south-east slope of the Konjuh Mountain.

In the gabbroic dykes, clinopyroxene is within the diopside-augite range of composition. Occasionally olivine, hypersthene and brown hornblende can be found. As a rule, pale-green amphibole of tremolite-actinolite composition forms on the account of augite (= alteration in greenschist facies).

The diabases, in several cases, display a porphyritic texture. An ophitic ground mass encloses coarser plagioclases, augites and more seldom amphiboles (replacing clinopyroxenes). In some thin-sections a transformation of the diabases to granoblastic amphibolites was observed. Conversion of augite to chlorite as a result of low grade metamorphism is also displayed. Massive diabase rocks are usually homogenous; the inhomogeneities are in the form of a network of thin veins of laumontite, prehnite and analcime, indicating a very low temperature regime of metamorphism.

In general, the mineral compositions of gabbros, diabases and dolerites do not reveal any significant difference, thus confirming a common origin. There is also no significant chemical difference between the gabbros and the diabases and basalts, which suggests that they have originated from the same magma source, resulting in the development of different textures depending on the depth within the crust in which they have crystallised.

Spilites occur as flood eruptions with characteristic pillow lavas on the top, indicating solidification under water. The largest flood eruption covers a surface of several square kilometers. The erupted rocks are usually situated on the top of the ophiolite suite, but in some places the basaltic lava was observed to have poured over the jurassic sediments.

The lavas are typical meta-basalts revealing a fine grained holocrystalline ophitic or amygdaloidal texture. Needle-shaped albite and augite are the main mineral components, augite being mostly converted to actinolite

or chlorite. Accessory minerals are epidote, clinozoisite, calcite, pumpellyite, and prehnite. Spilitic dykes originate from diabases by albitisation of calcic plagioclase (low temperature albite).

Locally, in a high temperature regime, parts of the upper crust rocks were transformed to amphibolites, especially in the surroundings of Vareš. The amphibolites retained characteristic spectra of trace elements and REE patterns, indicating a low significance of metasomatic processes in spite of the relatively high degree of metamorphism.

## 7. CHEMICAL COMPOSITION OF MANTLE ROCKS

Nine rocks were sampled from the exposed mantle sequences of the Bosnian ophiolites. Their chemical compositions are compiled in Table 2.

FREY (1984) used calcium to differentiate between undepleted (Ca-rich) and depleted (Ca-poor) mantle rocks, as calcium is mainly bound to clinopyroxene and this mineral is very often well preserved in the rocks. In the case of metamorphic changes the clinopyroxene is replaced by clinoamphibole, which retains at least part of the calcium in the crystal lattice. In some cases only calcium is extensively leached during metasomatic processes and fixed in calcite veins in adjacent rock areas. Our materials from the mantle sequences are modified by serpentinization and amphibolitisation, which probably have changed the primary Ca content. Therefore we decided to differentiate the rocks by means of their TiO<sub>2</sub> content in depleted and undepleted mantle material. Like Ca, Ti is an incompatible element which during melting gets depleted in mantle rocks due to the separation of Ti-rich partial melts of gabbroic composition. But in contrast to Ca, Ti is one of the elements with low mobility (COISH, 1977; PEARCE & CANN, 1973), and thus, during metamorphic overprinting, it should be retained in the mantle rocks even if Ca is removed.

Figure 2 shows that there are two groups of samples with respect to their TiO<sub>2</sub> content i.e. six peridotite samples with <0.06% TiO<sub>2</sub>, and three peridotite samples with >0.08% TiO<sub>2</sub>. The first group with less than 0.06% TiO<sub>2</sub> is representative for the depleted mantle (clinopyroxene-poor harzburgites) and the group with <0.08% TiO<sub>2</sub> is representative for the undepleted (or less depleted) mantle, i.e. clinopyroxene-bearing lherzolites.

Parallel to the depletion of TiO<sub>2</sub>, SiO<sub>2</sub> is being depleted and MgO enriched (Fig. 2) as a result of the enrichment of Fe-rich olivine during the progressive depletion of the mantle rocks with respect to clinopyroxene and orthopyroxene.

As to the trace elements, Ni and Co are significantly enriched in the depleted mantle, both being compatible elements with high distribution ratios between the residuum and partial melt. Usually they are incorporated in



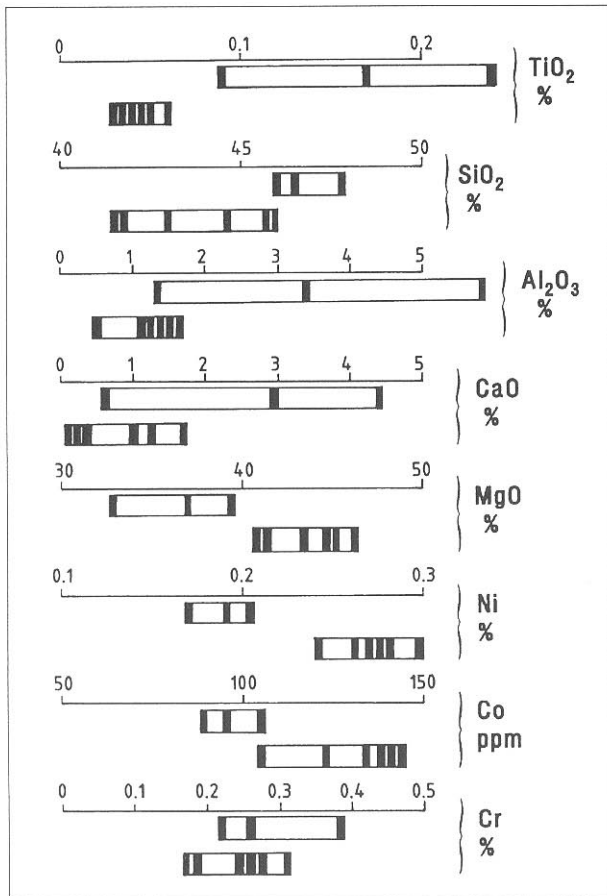


Fig. 2 Distribution of a few selected elements from nine mantle rock samples. legend: Upper bar - less depleted mantle (Iherzolites); Lower bar - more depleted mantle (harzburgites).

the olivine crystal lattice, replacing Mg. The same direction of enrichment should be valid for Cr, but this is not clearly expressed in the investigated mantle rocks. It is rather likely that Cr is incorporated in the spinels which are very unevenly distributed in the mantle rocks. This explains the variable Cr contents in the Harzburgite and Lherzolite analyses.

### 7.1. RARE EARTH ELEMENTS IN MANTLE ROCKS

The amount of rare earth elements (REE) in Iherzolitic mantle rocks is between 0.8 and 2.1 times that of chondrite. The average REE pattern for these rocks is shown in Fig. 3; it reveals the enrichment of heavy rare earth elements (HREE) in comparison to light rare earth elements (LREE). All REE are incompatible elements which are enriched in gabbroic partial melts compared with residual mantle material. LREE have a higher grade of incompatibility than the HREE, therefore they are more depleted than the HREE in the residual mantle material. The REE pattern for Iherzolite shown in Fig. 3 is typical for moderately depleted mantle rocks.

The amount of REE in harzburgites is, as expected, lower than in Iherzolites, lying between 0.2 and 0.6 times the chondrite content (Fig. 3). The weak enrichment of LREE, responsible for the V-shaped REE dis-

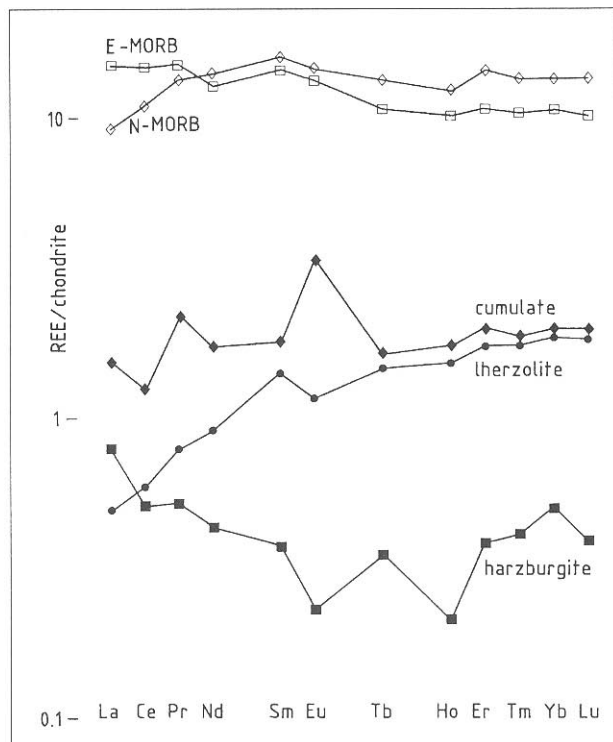


Fig. 3 Average REE patterns normalized on a chondrite basis (WAKITA et al. 1971) for different types of rocks occurring in the Jurassic ophiolite suite of Bosnia and Herzegovina.

tribution pattern, has been observed in many depleted mantle rocks, but it is not yet exactly explained (FREY, 1984). The widespread hypothesis for the explanation of this V-shaped distribution of REE is that H<sub>2</sub>O- and CO<sub>2</sub>-connected metasomatic processes, which cause serpentinization and - to a lesser degree - amphibolitisation of mantle material, are also responsible for the enrichment of LREE. These H<sub>2</sub>O and CO<sub>2</sub>-rich solutions can transport the LREE better than HREE. This process, which should be widespread, influencing more or less all the mantle rocks, can change significantly only the REE patterns of strongly depleted mantle rocks, because in these the primary amount of REE is already extremely low.

The negative Europium anomaly is visible in both the average REE patterns, it is weak in Iherzolites and stronger in harzburgites. Negative Eu anomalies develop in mantle material during the depletion process because Eu is selectively enriched in partial mantle melts of gabbroic composition. Therefore it is to be expected that the less depleted mantle (Iherzolites) reveal on average a weaker negative Eu anomaly than the more depleted mantle (harzburgites).

Figure 4 shows the individual REE patterns of three mantle rocks with a strongly developed negative Eu anomaly, one Iherzolite and two harzburgites. This figure demonstrates that the depletion of Eu can also be strong in individual Iherzolite samples, although on average it is stronger in harzburgites. Also interesting is that the three mantle rocks show a well developed nega-

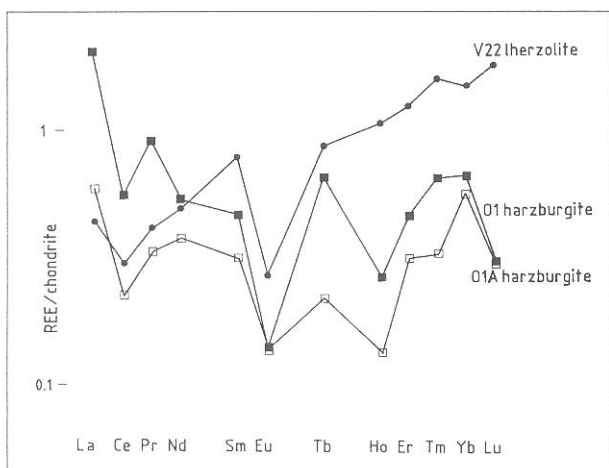


Fig. 4 Individual REE patterns normalized on a chondrite basis (WAKITA et al., 1971) for three mantle rocks with a pronounced negative Eu anomaly; two harzburgites and one lherzolite.

tive Ce anomaly additionally to a negative Eu anomaly. This Ce anomaly is formed during serpentinisation processes by means of sea water, as the sea water REE spectrum reveals an extremely strong negative Ce anomaly, which is reflected by the composition of minerals formed in contact with sea water. It is not clear why only these three samples with a negative Eu anomaly also show a negative Ce anomaly; it should be tested with a larger number of samples if there is some interdependence between depletion by means of partial melt formation (Eu-depletion) and by the serpentinization process (Ce-depletion). Theoretically this trend can be expected, as depletion of the mantle because of partial melting enriches olivine in the residual material, and olivine is the first mineral to react with sea water and form secondary minerals.

## 8. CHEMICAL COMPOSITION OF CUMULATE ROCKS

The partial melt, created in the mantle, undergoes fractional crystallization in axial magma chambers below rift zones. Cumulate rocks with an intercumulus phase than form, which vary greatly in their composition, which is dependent upon the composition of the melt from which they precipitate, the stage of differentiation of the cumulate phase, the intercumulate melt relationships, and the mixture of remaining melts with batches of fresh primitive mantle melt. The pressure variations between magma chambers do not seem to be an important factor in magma differentiation at constructive plate margins, because differentiation happens in this case under low pressure in shallow crustal magma chambers.

Figure 5 shows the frequency diagrams of some elements in mantle rocks, cumulate rocks and overlying gabbros and basalts. From these frequency diagrams it can be seen that the contents of incompatible elements Si, Ti, and V increase from mantle rocks, via cumulates

to maximum levels in the upper crust gabbros and basalts. On contrast, the levels of compatible elements Mg, Cr, Ni, and Co decrease in the same direction.

There is always an area of overlap between the composition of mantle and cumulates which reveal an ultramafic composition, as can be seen in Fig. 5. Thus cumulate ultramafic rocks can only be distinguished with reservation from mantle ultramafic rocks by means of bulk chemical composition, if they have lost their cumulate texture by metamorphic or tectonic overprints.

An approach to distinguish between mantle rocks and ultramafic cumulate rocks is given by IRVINE & FINDLAY (1972), who used the NiO vs Cr<sub>2</sub>O<sub>3</sub> plot for discrimination. Most mantle peridotites with spinel as the pure accessory phase plot below 0.5 wt.% Cr<sub>2</sub>O<sub>3</sub> and above 0.2 wt.% NiO. Cumulate ultramafic rocks occur below 0.2 wt.% NiO.

Figure 6 shows the plot of Ni against Cr with the division line as suggested from IRVINE & FINDLEY (1972). All the mantle lherzolites and harzburgites except one cluster in the field determined for mantle rocks. Cumulate rocks cluster without exception in the field determined for cumulate rocks. This shows that, provided that there is no chromite enrichment or lateritisation of olivine-rich rocks, the Ni/Cr plot is suitable for differentiation between cumulate rocks and refractory mantle rocks.

Geochemical conclusions relating to the primary setting of oceanic crust which was later incorporated as ophiolites in island arc or continental margin crust, are usually drawn from the upper crust section, represented by the basalts. Only a plot suggested by SERRI (1981) uses the cumulate section of ophiolites to detect the original setting of ancient oceanic crust. The cumulates in this plot are divided into two groups, one with low Ti content which is formed under the influence of a subducted slab (island arcs, incipient parts of back arcs) and another with high Ti content, formed without the influence of a subducted slab (mid-ocean ridges, evolved parts of back-arc spreading systems). The differentiation between the two types of cumulates requires the comparison of the rocks at the same level of fractionation, therefore the other branch of the diagram is the cumulate fractionation factor FeO/FeO+MgO. To a certain degree recent materials are available for testing the plot and for comparison with ophiolitic samples. In recent years several holes were drilled by the Ocean Drilling Program into cumulate rocks, though in all cases in the obducted oceanic crust, never in the in-situ cumulate rocks (LAGABRIELLE & CANNAT, 1990; ROSS & ELTHON, 1993; MEVEL & CANNAT, 1991).

In the diagram shown in Fig. 7 cumulates from our investigation are plotted together with the cumulates from a recent mid-oceanic spreading zone. Both groups of cumulates follow the same fractionation trend of high Ti-ophiolites. Thus they obviously formed independently from the influence of a subducted slab.

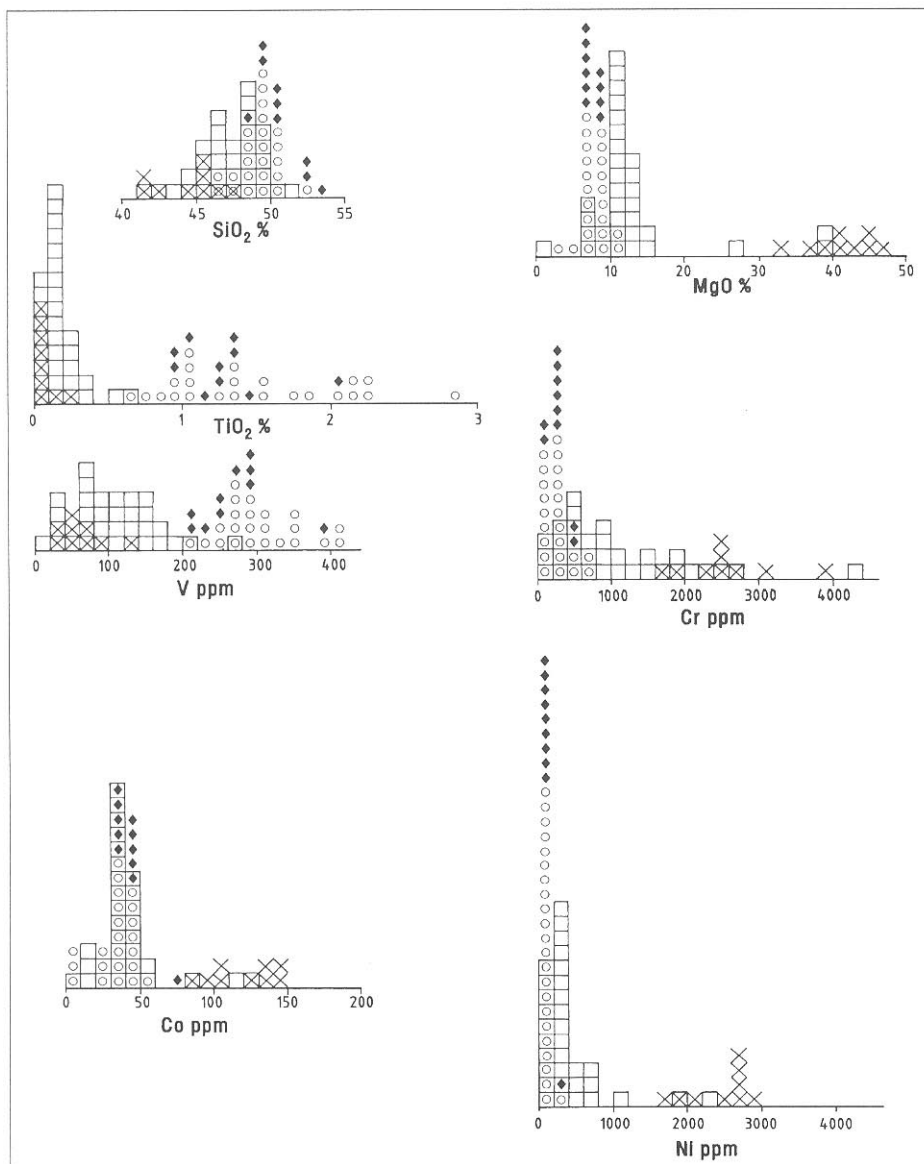


Fig. 5 Frequency diagrams for selected elements in mantle peridotites (x), cumulate rocks (□) and upper crust rocks (○ for N-MORB and ♦ for E-MORB).

### 8.1. RARE EARTH ELEMENTS IN CUMULATE ROCKS

The ratio of REE to chondrite for cumulate rocks is in the range 0.4 - 5.8. For mantle rocks of the same ophiolite group this ratio is 0.2 - 2.1. As expected, on average, the incompatible REE are enriched in the cumulates in comparison to mantle rocks, but as is the case for other incompatible elements, there is a strong overlap of the REE contents of mantle rocks and cumulate rocks. Figure 3 shows the average chondrite-normalized REE pattern for the 33 analysed cumulate rocks.

The positive Eu anomaly, present in the average REE plot of cumulate material, was calculated for every individual cumulate rock. It is present in all the cumulate rocks, varying from 0.12 - 10.5, with the median at 1.4.

Crystallising plagioclases in the magma chamber selectively incorporate Europium in the crystal lattice, thus producing a positive Eu anomaly in plagioclase-bearing cumulate rocks. The density of plagioclase is

very similar to the density of the melts in axial magma chambers (ELTHON, 1984), therefore plagioclases can remain suspended for longer periods of time, as reflected in the accreted layers before they settle within cumulate rocks. The cumulate rocks from the Bosnian ophiolites witness the fractionation of plagioclase very early in the crystallization process. This is the plagioclase occurring as a cumulate, but the intercumulus phase also contains plagioclase because of its buoyancy in the magmatic melt. For this reason plagioclases occur in all the cumulate rocks including the ultramafic cumulates, or at least they were present before metamorphic changes took place. Some of these rocks were, as already described, transformed to amphibolites, but this process obviously did not change their REE patterns.

The early accumulation of plagioclase is characteristic for magma chamber processes under diverging oceanic plate boundaries. It is in accordance to the conclusions drawn from Fig. 7 that this oceanic crust was formed out of the influence of a subducting slab. DOS-TAL & MUECKE (1978) investigated the REE con-

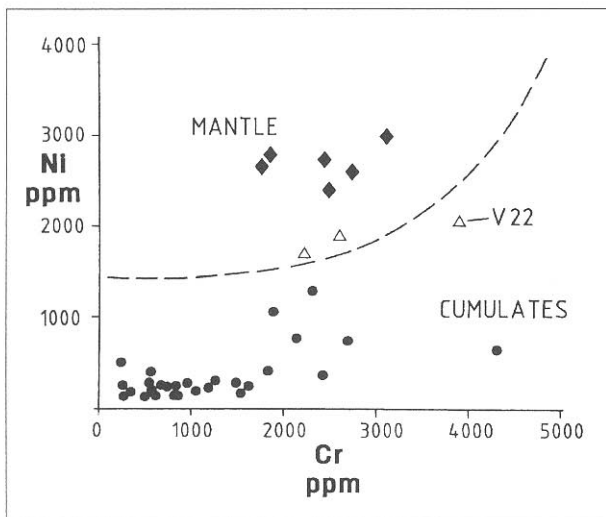


Fig. 6 Ni/Cr plot for discrimination between mantle rocks and cumulate rocks after IRVINE & FINDLEY (1972). Legend:  $\circ$  - cumulate rocks;  $\Delta$  - mantle thersolites;  $\blacklozenge$  - mantle harzburgites.

tents of serpentinised cumulate peridotites from the Mid-Atlantic Ridge, and these peridotites are also characterized by a positive Eu-anomaly, indicating the presence of plagioclase.

## 9. CHEMICAL COMPOSITION OF THE UPPER PART OF THE OPHIOLITE SEQUENCE

Thirty three samples were analyzed from the upper crustal part of the ophiolite sequence. Seven of them were recognized as basalts and ten as diabases, but the remaining sixteen samples are amphibolites, and they were assigned to the subvolcanic and volcanic ophiolite units, based on their position within the ophiolite complex.

Figures 8, 9, and 10 show eight x/y plots and four triangular diagrams which are developed from modern

basalts and suggested for discrimination between basalts from different tectonic settings. The applicability of these diagrams for metamorphosed rocks from ophiolite complexes is still debated and depends on various factors, e.g. the grade of metamorphism, and the bonding of the discriminative elements in the original material etc. Geochemical investigations of rocks from the Semail ophiolite (LIPPARD et al., 1986) have shown, that at least in the case of low metamorphic overprint most of the geochemical discrimination diagrams can be used for determining the geological setting of the ancient oceanic crust.

In all the diagrams which we used for the upper part of the ophiolite suite in Bosnia the predominant part of the samples is situated in the Mid-ocean-ridge-basalt (MORB) field. This indicates that these rocks are not significantly changed by metasomatism. In several plots some samples fall out of the MORB field and trend towards the direction of island arc tholeiites or plume MORB (E-MORB), but in these cases the position is mostly close to the N-MORB type.

The comparison of splitized rocks with amphibolitized rocks results in the same average chemical composition, another hint to the conclusion that the changes caused by metasomatic processes must have been very low in the investigated subvolcanic and volcanic sequence.

### 9.1. RARE EARTH ELEMENTS IN THE SUBVOLCANIC AND VOLCANIC SEQUENCE

Figure 11a and b show plots of La against Lu and Ce against Yb for chondrite-normalized rocks of the upper crustal sequence. It can be seen from these figures that the larger amount of the upper crustal rocks reveal a depletion of  $La_{(cn)}$  in comparison to  $Lu_{(cn)}$  and of  $Ce_{(cn)}$  in comparison to  $Yb_{(cn)}$ , respectively, i.e. a depletion of LREE in comparison with HREE. Ten samp-

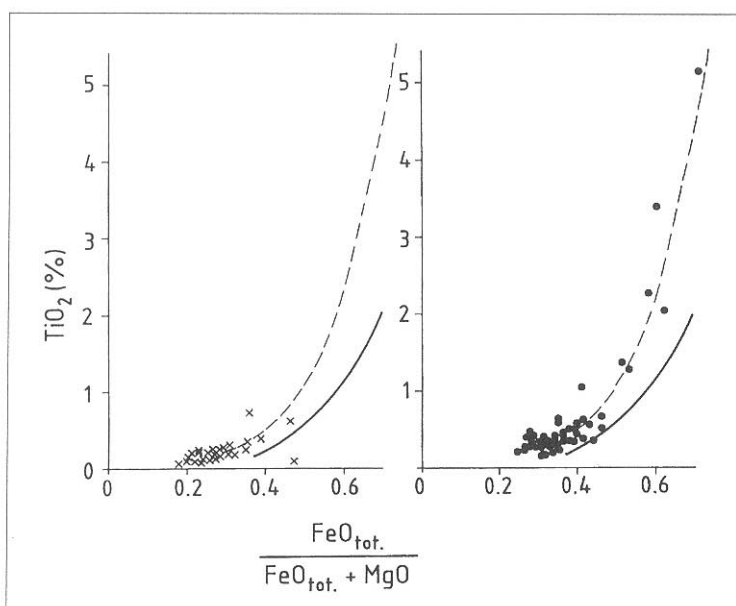


Fig. 7 The plot of  $TiO_2$  against the cumulate fractionation factor ( $FeO_{tot.}/FeO_{tot.}+MgO$ ) from SERRI (1981). Legend:  $\times$  - cumulate rocks from ophiolite suite in Bosnia and Herzegovina;  $\bullet$  - cumulate rocks from Mid Atlantic Ridge 23° N (own unpublished results); ----- - boundary between low-Ti and high-Ti ophiolite types; — - estimated cumulate fractionation trend.

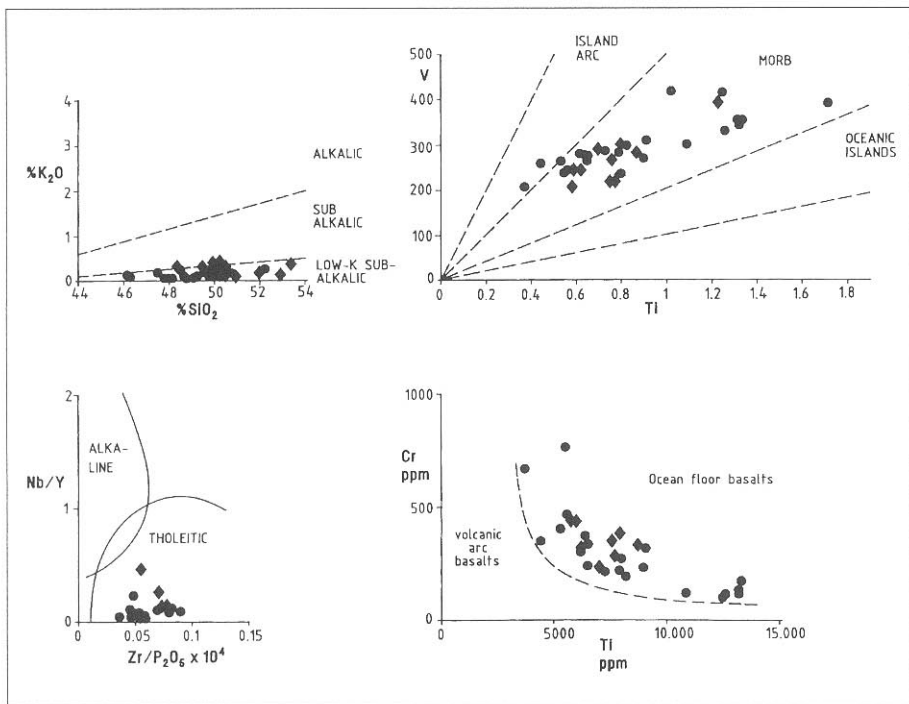


Fig. 8 x/y plots for discrimination between different types of basalt: a) after MIDDLEMOST (1975); b) after SHERWALS (1982); c) after FLOYD & WINCHESTER (1975); d) after GARCIA (1978). Legend: ● - N-MORB; ◆ - E-MORB.

les in the La/Lu<sub>(cn)</sub> plot and twelve samples in the Ce/Yb<sub>(cn)</sub> plot show a weak enrichment of LREE compared to HREE. Typical for MORB from constructive plate margins is a slight depletion of LREE in comparison with HREE, due to the lower incompatibility of HREE compared to LREE. If we take the La-enriched samples from Fig. 11 a as a separate group and calculate the average values for the two groups, then the REE spectra for these two groups (shown in Fig. 3) clearly demonstrate the enrichment of LREE in one group and depletion of LREE in the other.

Not only is the LREE depletion typical for REE patterns of MORB from constructive plate margins but

also the overall REE enrichment of one order of magnitude if compared to the chondrite REE content. This is also true for most samples from the upper crust in this study. A small number of the upper crust samples were aberrant, but such REE patterns were observed as well in some situations at constructive plate margins and they have been explained by the involvement of deeper parts of the mantle at the formation of MORB. The formation of such “enriched” MORB has been observed at constructive plate margins in locations where large fracture zones, deeper than the plate boundary, activated deeper parts of mantle to contribute to the magmatic activity. The deeper parts of the mantle are probably

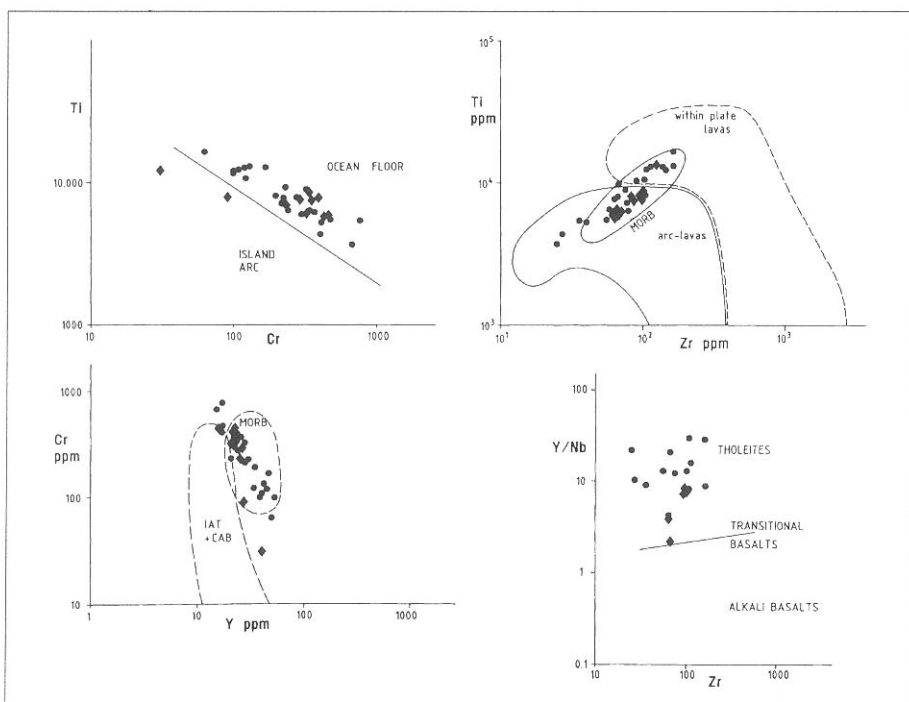


Fig. 9 x/y plots for discrimination between different types of basalt: a) after PEARCE (1975); b) after PEARCE (1980); c) after PEARCE et al. (1984); d) after LIPPARD et al. (1986). Legend: ● - N-MORB; ◆ - E-MORB;

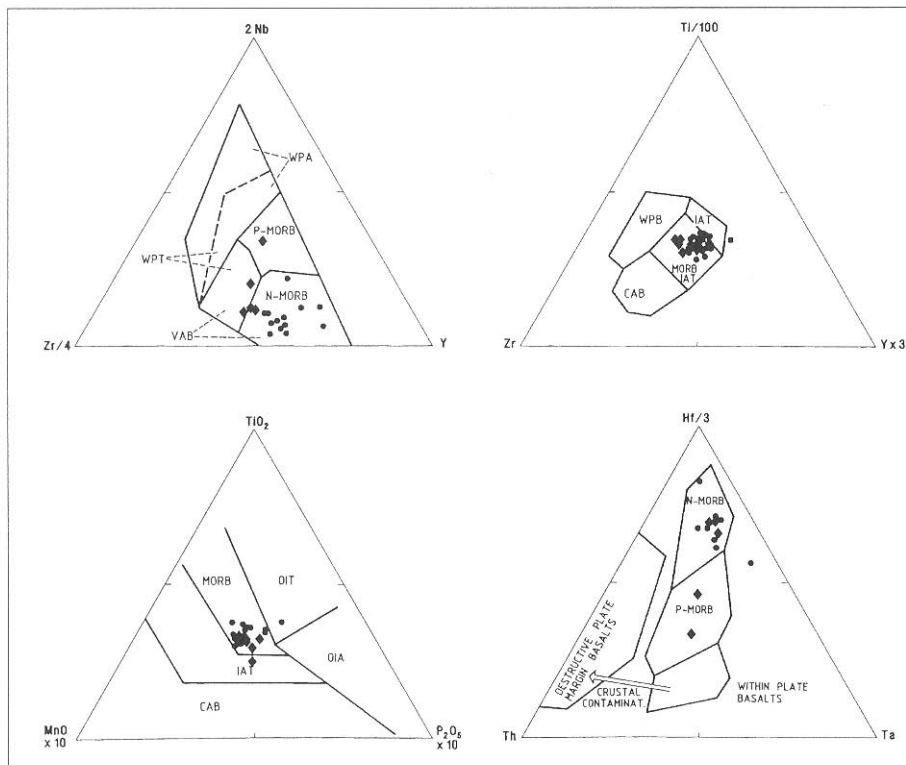


Fig. 10 Triangle diagrams for discrimination between different types of basalt: a) after MESCHEDE (1986); b) after PEARCE & CANN (1973); c) after MULLEN (1983); d) after WOOD et al. (1979). Legend: ● - N-MORB; ◆ - E-MORB. Abbreviations: WPA - within plate alcaic; WPT - within plate tholeite; VAB - Volcanic arc basalts; MORB - mid ocean ridge basalt; P-MORB - plume MORB; N-MORB - normal MORB; WPB - within plate basalts; IAT - island arc tholeites; CAB - calc alkaline basalts; OIT - oceanic island tholeite; OIA - oceanic island alcaic.

more similar to the initial magma composition, i.e. somewhat lesser depleted than the upper parts of the mantle in the areas of plate divergency in which most of partial melting takes place.

Recently at the East Pacific Rise enriched MORB was observed in the vicinity of large fracture zones (BELLIENI et. al., 1992). We assess the local occurrence of enriched MORB as additional evidence for a deep fracture zone which has cut and dislocated the Jurassic constructive plate boundary of the Tethyan Ocean Basin in the area of Bosnia. The other evidence for fracture zone cutting and dislocation of the constructive plate boundary in this area are the cataclased areas in the cumulate part and the absence of a well developed sheeted dyke complex.

The enrichment of light REE parallels the enrichment of other incompatible elements in "enriched" MORB, like K, Ba, and less significantly Rb and Sr. This enrichment could also have been caused by other processes; the incompatible elements, for example, also become enriched in the residual melt in the magma chamber. The unequivocal evidence for two different mantle sources contributing to the formation of the upper crust rocks can be gained only from the changing ratios of LREE to HREE were already shown in Fig. 11. Figure 12 shows the Ce against Zr plot. Ce and Zr are of similar incompatibility and the development of the enrichment during liquid/solid differentiation in the crustal magma chamber is parallel for these two elements. The enrichment of Ce is stronger in comparison to Zr in basalt samples derived from enriched upper mantle rocks. The investigated samples from Bosnia and Herzegovina plot along different regression lines.

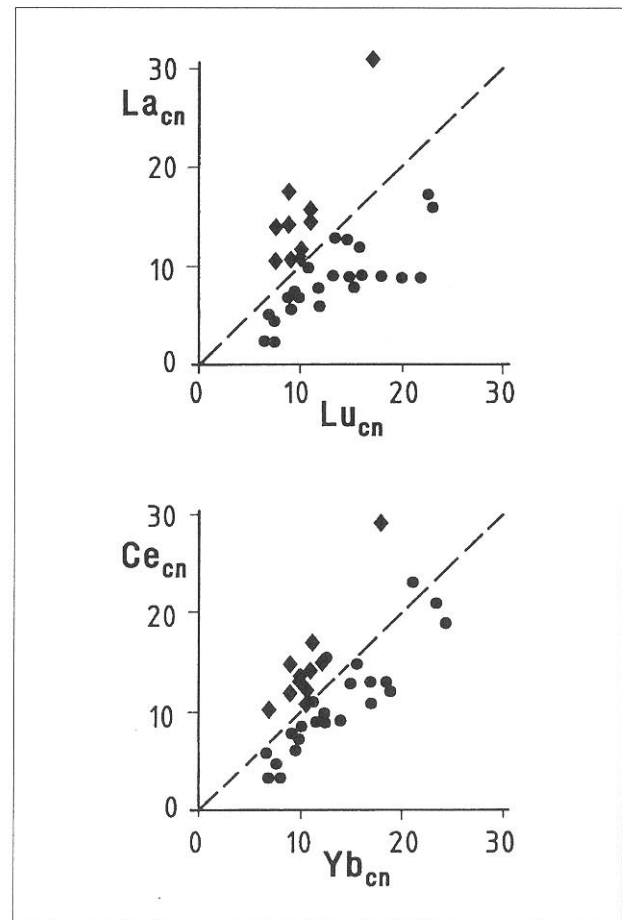


Fig. 11 Plots of La against Lu and Ce against Yb for upper crust rocks. Legend: ● - normal MORB ( $La_{cn}/Lu_{cn}$  smaller than 1); ◆ - enriched MORB ( $La_{cn}/Lu_{cn}$  larger than 1).

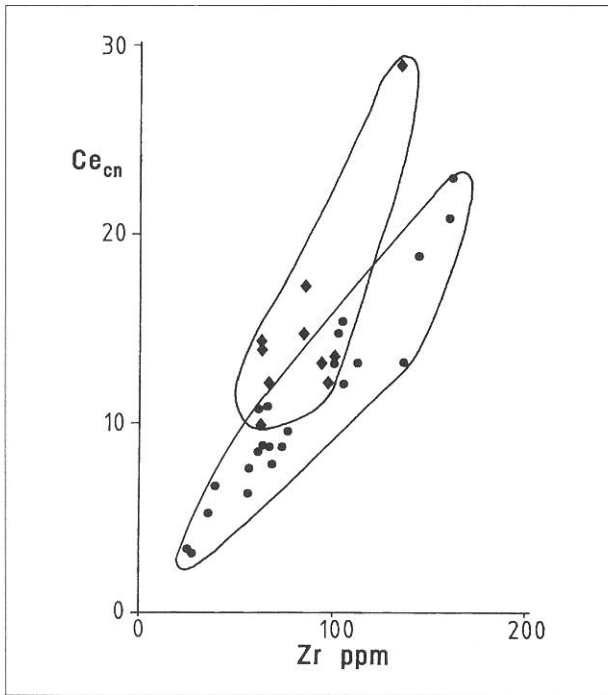


Fig. 12 Plot of Ce against Zr for upper crust rocks. Legend: ● - normal MORB; ◆ - enriched MORB.

This indicates that two magmas of different primary compositions have contributed to their formation.

The plot of Th/Yb against Ta/Yb is using the RE element Yb as the denominator which largely eliminates variations due to partial melting and differentiation in the magma chamber, showing with greater probability the tectonic setting of the investigated upper crustal rocks than do simple element plots (PEARCE, 1983). Th is transported from the subducted slab in aqueous and Si-rich solutions and in this way it becomes enriched in basalts in a back arc environment. The

plot of Fig. 13 shows that the ophiolites in Bosnia developed on diverging oceanic plate boundaries from a moderately depleted mantle without any influence of subduction. The few samples which we determined as enriched point to an enriched mantle source, but they are still in the range similar to the normal MORB.

### 10. CONCLUSIONS

The ophiolite suite is composed of:

Mantle rocks, which comprise lherzolites and some harzburgites. The chemical composition of the harzburgites shows a slight LREE enrichment and consequently V-shaped REE patterns which could have originated from a metasomatic mantle overprint. The negative Eu anomaly is characteristic for all mantle rocks and is stronger in harzburgites than in lherzolites. Strong negative Ce anomalies are developed in samples with a strong Eu anomaly. The Ce anomalies are explained by serpentinization in contact with sea water.

Cumulate rocks, from ultramafic to gabbroic. A zone of tectonic destruction passes through the cumulate sequence. The cumulates are locally transformed to amphibolites, the remaining cumulates showing only a weak metamorphism of the zeolite type. The possibility to geochemically distinguish the cumulates from mantle and upper crust material centres on the Cr to Ni ratio and, with a higher rate of success, the distinct positive Eu anomaly in the cumulate rocks. This anomaly which develops due to the early crystallisation of plagioclase, (which is one of the characteristics of MOR-type ophiolites) is additionally increased because of the buoyancy of the plagioclases, which remain suspended in a magma chamber for long periods of time and therefore are present in the intercumulus phase of all the cumulate rocks.

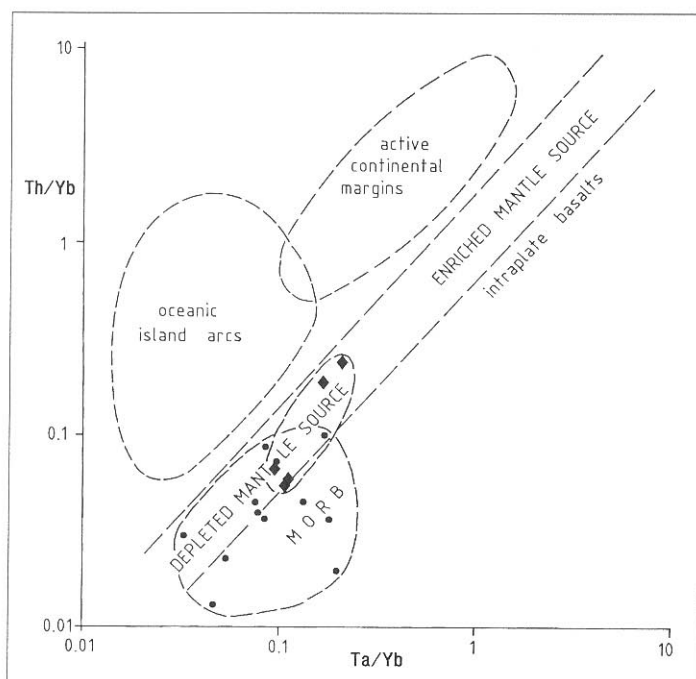


Fig. 13 Plot of Th/Yb against Ta/Yb as suggested from PEARCE (1983). Legend: ● - normal MORB; ◆ - enriched MORB.

Upper crustal rocks comprise basalts, gabbros and diabases. Instead of a sheeted dyke complex, a tectonically strongly disrupted area is present which is comparable to the situation in the Ligurian ophiolites of the same age. Also here, as in the cumulate rocks, most rocks passed through a weak metamorphism; only locally, especially in the area around Vareš, the rocks suffered high metamorphic changes of the amphibolite facies. The rocks geochemically reveal the characteristics of N-MORB formed from a moderately depleted mantle at a constructive plate boundary. The ratio of Ta to Th; the most sensible indicator for the influence of subduction, shows that these upper crustal rocks are free from the contribution of a subduction process. The weak enrichment of LREE in a smaller portion of the upper crustal rocks could be due to the influence of a less depleted mantle. The presence of enriched MORB (E-MORB) together with normal MORB (N-MORB), the tectonized area in the cumulate sequence, the substitution of the sheeted dyke complex by a strongly tectonised area and the local occurrence of high grade metamorphic rocks within the weakly metamorphosed ophiolite, show that this ophiolite was formed by means of spreading of young oceanic crust close to the intersection of a spreading ridge and a transform fault.

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