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The composition of the continental crust*

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Abstract—A new calculation of the crustal composition is based on the proportions of upper crust (UC) to felsic lower crust (FLC) to mafic lower crust (MLC) of about 1:0.6:0.4. These proportions are derived from a 3000 km long refraction seismic profile through western Europe (EGT) comprising 60% old shield and 40% younger fold belt area with about 40 km average Moho depth. A granodioritic bulk composition of the UC in major elements and thirty-two minor and trace elements was calculated from the Canadian Shield data (Shaw et al., 1967, 1976). The computed abundance of thirty-three additional trace elements in the UC is based on the following proportions of major rock units derived from mapping: 14% sedimentary rocks, 25% granites, 20% granodiorites, 5% tonalites, 6% gabbros, and 30% gneisses and mica schists. The composition of FLC and MLC in major and thirty-six minor and trace elements is calculated from data on felsic granulite terrains and mafic xenoliths, respectively, compiled by Rudnick and Presper (1990). More than thirty additional trace element abundances in FLC and MLC were computed or estimated from literature data.

The bulk continental crust has a tonalitic and not a dioritic composition with distinctly higher concentrations of incompatible elements including the heat producing isotopes in our calculation. A dioritic bulk crust was suggested by Taylor and McLennan (1985). The amount of tonalite in the crust requires partial melting of mafic rocks with about 100 km thickness (compared with about 7 km in the present MLC) and water supply from dehydrated slabs and mafic intrusions. At the relatively low temperatures of old crustal segments MLC was partly converted into eclogite which could be recycled into the upper mantle under favourable tectonic conditions. The chemical fractionation of UC against FLC + MLC was caused by granitoid partial melts and by mantle degassing which has controlled weathering and accumulation of volatile compounds close to the Earth's surface.

**FORMER ESTIMATES OF CRUSTAL COMPOSITION;
SEISMIC CRUSTAL MODEL**

The general acceptance of the definition of the continental crust as the continental upper part of the silicate Earth above the Mohorovičić discontinuity dates back to the fifties of this century (Poldervaart, 1955). Earlier authors as Clarke (1924) and Goldschmidt (1933) reported average chemical compositions of magmatic rocks or of what the latter author called the "lithosphere." Both averages were restricted to major units of the upper continental crust of our present definition.

In this investigation we conclude from seismic properties on the thickness of the continental crust and the size and compositional characteristics of its major units. During the recent one and a half decade, refraction seismic ray velocities have been evaluated on a 4800 km long almost continuous traverse through Europe from the North Cape to Tunisia of which we used ~3000 km (Ansorge et al., 1992). The European Geotraverse (EGT) was designed to encompass the succession of tectonic provinces from the oldest known Archean to those still active today. The tectonic provinces occur in succession from the north to the south as well as in time. The first step in understanding how the continental lithosphere of Europe formed was a survey of physical properties (density, etc.) in

the geometry of the crust. EGT was long and variable enough to be representative of a typical crustal section. It comprises the Archean and Proterozoic Fennoscandian Shield with 45.5 km average Moho depth, the Late Proterozoic and Phanerozoic fold belts of Central Europe with 30 km crustal thickness, and the young Alpine orogen with its deep roots from the collision of two continents. The proportion of 60% old shield and 40% younger fold belts is representative of the state of the continental crust in different continents. A combination of the two crustal sections of different age gives an average crustal thickness of 40 km.

A travelttime interpretation of the seismic refraction profile through the Fennoscandian Shield (FENNOLORA), the transition from the Svecofennian Province in the Sorgenfrei-Tornquist Zone to the Danish and North German Basins (EUGENOS) and the younger fold belts in Central Europe (EUGEMI and EGT-S 86) is presented in Fig. 1. At the right edge of the lower part of this cross section, Proterozoic and Phanerozoic Central Europe merges into the deep Alpine orogen in which the European and African crusts collided. For better presentation the simplified profile was divided into two parts.

In Fig. 1 the continental crust consists of two major layers. The upper and lower crust can be conventionally separated according to P-wave velocities of less and more than 6.5 km/s. The interface occurs at almost 20 km depth in the upper part of Fig. 1 and is more variable in depth (20–50 km) in the

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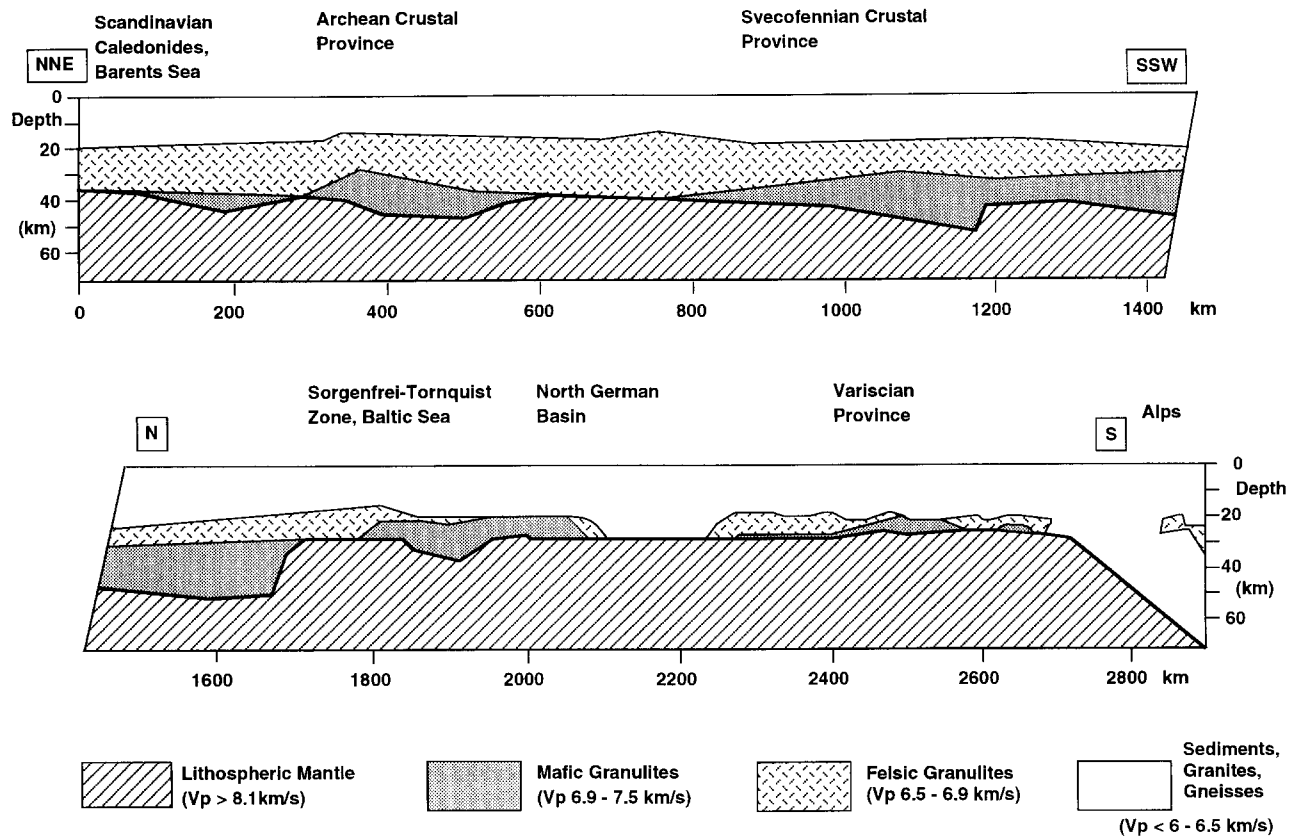


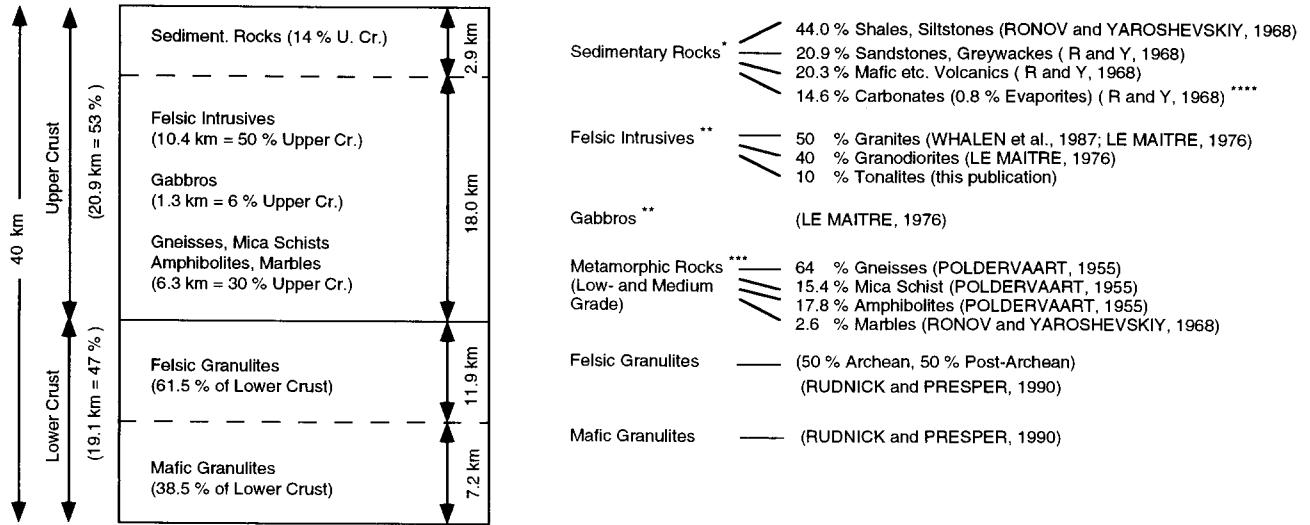
FIG. 1. Simplified cross section of the crustal structure of the Baltic Shield and central Europe based on refraction seismic P-velocities derived from Figs. 3-4, 3-6, 3-9 and 3-11 in Ansgore et al. (1992) and from the detailed interpretations of FENNOLORA, EUGENO-S (Line 1), EUGEMI and EGT-S86 by Guggisberg et al. (1991), Aichroth et al. (1992), and Ye (1992).

younger provinces presented in Fig. 1 (lower part). Superimposed on this basically two-layered crust are substantial lateral variations of the velocity distribution and layer thickness. Details in the uppermost crust of the Scandinavian profile are questionable because of large distances between the shotpoints in that part of the EGT. The major rocks below the interface at 20 km average depth and above the Moho have been identified as granulites (for correlation of seismic properties with rock species see Kern and Schenk, 1988; Kern, 1990; Rudnick, 1992). The identification of major crustal rocks in the EUGEMI part of EGT was improved by the investigation of crustal xenoliths in the Tertiary volcanic rocks (Mengel et al., 1991). Luosto et al. (1989) observed that the lower crust of the Scandinavian Shield is separated into a felsic upper part and a mafic lower part (the latter with more than 6.8 km s^{-1} P-wave velocity) at an additional interface. Mafic granulites mainly from former gabbroic intrusions are recognized as the most abundant rocks in this lowest crustal layer of 7 km average thickness. Confirmation of this identification as mafic granulites comes from areas of the world where these are sampled by volcanism and investigated as xenoliths (Rudnick 1992). Rare metapelitic garnet schists cannot be discriminated from the abundant mafic granulites by their seismic velocities (Kern, 1990). In the younger fold belts of Central Europe, mafic granulites occur locally as a

voluminous body but more as a thin layer above the Moho. Because of difficulties to find out the thickness of the sedimentary top layer of the EGT crust we have used the estimate by Ronov and Yaroshevskiy (1968) of a 2.9 km thick unit of sedimentary rocks in the continental crust. This was based on drilling and mapping. In the young fold belt of Central Europe, sedimentary basins locally increase to more than 10 km depth.

The upper continental crust is much better exposed for sampling and investigation than the lower crust. Two comprehensive chemical studies on the composition of the upper crust reported comparable results (Shaw et al., 1967, 1976, 1986; Taylor and McLennan, 1985). Their results differ distinctly in Be, B, Cu, Zn, Ba, Ta, and Bi. Shaw et al. (1967, 1976) analysed 8,512 rocks from large areas of the Canadian Shield mainly in composite samples. They grouped them into six lithologic varieties. Taylor and McLennan (1985) based their minor and trace element data on analyses of shales, loesses, and greywackes in the assumption that the processes of erosion and sedimentation produced an average sample of the exposed crust. They corrected for element fractionation during weathering and sedimentation from REE distribution and element ratios, well known from isotope geochemistry. Their major element data were adopted from those on the Canadian Shield composition and their data on Zn, Cd, Tl, Pb, and Bi

Standard Profile of the Continental Crust (EGT)
 62 % Archean - Proterozoic Crust (45.5 km thick)
 38 % Proterozoic - Phanerozoic Crust (30 km thick)
 (Mass of Bulk Cont. Crust: 2.13 x 10¹⁹ t)



* Abundances in 73 % Geosynclines and 27 % Platforms according to RONOV and YAROSHEVSKIY (1968)
 ** Abundances according to DALY (1933) and MOORE (1959)
 *** Abundances according to RONOV and YAROSHEVSKIY (1968)
 **** Abundance of Carbonates reduced from 17.6 to 14.6 % according to Carbon Isotope Balance

FIG. 2. Standard profile of the continental crust derived from the 3000 km long European Geotraverse generalized on the basis of worldwide mapping, petrological studies and chemical balances (Table 5 etc.).

Table 1 Element concentrations (in ppm) in the Upper Continental Crust (UC) and the Lower Continental Crust (LC) (For references see footnotes in Table 2)

	UC	LC	UC/LC		UC	LC	UC/LC		UC	LC	UC/LC
Si	303480	271330	1.1	Ce	65.7	53.1	1.2	Yb	1.5	2.5	0.60
Al	77440	82120	0.94	Ni	18.6	99	0.19	U	2.5	0.93	2.7
Fe	30890	57060	0.54	Nd	25.9	28.1	0.92	Br	1.6	0.28	5.7
Ca	29450	48600	0.61	La	32.3	26.8	1.2	Ge	1.4	(1.4)	1.0
Na	25670	21200	1.2	Cu	14.3	37.4	0.38	Be	3.1	1.7	1.8
Mg	13510	31550	0.43	Co	11.6	38	0.31	Mo	1.4	0.6	2.3
K	28650	13140	2.2	Y	20.7	27.2	0.76	Eu	0.95	1.6	0.59
Ti	3117	5010	0.62	Nb	26	11.3	2.3	Ta	1.5	0.84	1.8
C	3240	588	5.5	Li	22	13	1.7	I	1.4	0.14	10
P	665	872	0.75	Sc	7	25.3	0.28	Ho	0.62	0.99	0.63
Mn	527	929	0.57	Ga	14	17	0.82	W	1.4	0.6	2.3
S	953	408	2.3	Pb	17	12.5	1.4	Tb	0.50	0.81	0.62
Ba	668	568	1.2	B	17	5	3.4	Tl	0.75	0.26	2.9
F	611	429	1.4	Th	10.3	6.6	1.6	Lu	0.27	0.43	0.63
Cl	640	278	2.3	Pr	6.3	7.4	0.85	Sb	0.31	0.30	1.0
Sr	316	352	0.90	Sm	4.7	6.0	0.78	Cd	0.102	0.101	1.0
Zr	237	165	1.4	Hf	5.8	4.0	1.5	Ag	0.055	0.080	0.69
Cr	35	228	0.15	Gd	2.8	5.4	0.52	Bi	0.123	0.037	3.3
V	53	149	0.36	Dy	2.9	4.7	0.62	Se	0.083	0.170	0.47
Rb	110	41	2.7	Sn	2.5	2.1	1.2	In	0.061	0.052	1.2
Zn	52	79	0.66	Cs	5.8	0.8	7.3	Hg	0.056	0.021	2.7
N	83	34	2.4	As	2.0	1.3	1.5				

Table 2 Element concentrations in the Continental Crust (For major elements as oxides see Table 3 and for references see footnotes)

O	47.2 % ^a	Nd	27 ppm ^a	Mo	1.1 ppm ^o
Si	28.8 % ^a	Cu	25 ppm ^a	Br	1.0 ppm ^p
Al	7.96 % ^a	Co	24 ppm ^a	W	1.0 ppm ^q
Fe	4.32 % ^a	Y	24 ppm ^a	I	800 ppb ^r
Ca	3.85 % ^a	Nb	19 ppm ^a	Ho	800 ppb ^a
Na	2.36 % ^a	Li	18 ppm ^a	Tb	650 ppb ^a
Mg	2.20 % ^a	Sc	16 ppm ^a	Tl	520 ppb ^s
K	2.14 % ^a	Ga	15 ppm ^a	Lu	350 ppb ^a
Ti	4010 ppm ^a	Pb	14.8 ppm ^a	Tm	300 ppb ^g
C	1990 ppm ^b	B	11 ppm ^f	Sb	300 ppb ^t
P	757 ppm ^a	Th	8.5 ppm ^a	Se	120 ppb ^u
Mn	716 ppm ^a	Pr	6.7 ppm ^g	Cd	100 ppb ^s
S	697 ppm ^b	Sm	5.3 ppm ^a	Bi	85 ppb ^s
Ba	584 ppm ^c	Hf	4.9 ppm ^a	Ag	70 ppb ^v
F	525 ppm ^d	Gd	4.0 ppm ^a	In	50 ppb ^w
Cl	472 ppm ^d	Dy	3.8 ppm ^g	Hg	40 ppb ^x
Sr	333 ppm ^a	Cs	3.4 ppm ^h	Te	(5) ppb ^y
Zr	203 ppm ^a	Be	2.4 ppm ⁱ	Au	2.5 ppb ^z
Cr	126 ppm ^a	Sn	2.3 ppm ^k	Pd	0.4 ppb ^{aa}
V	98 ppm ^a	Er	2.1 ppm ^g	Pt	0.4 ppb ^{aa}
Rb	78 ppm ^a	Yb	2.0 ppm ^a	Re	0.4 ppb ^{bb}
Zn	65 ppm ^a	As	1.7 ppm ^l	Ru	0.1 ppb ^{aa}
N	60 ppm ^c	U	1.7 ppm ^a	Rh	0.06 ppb ^{aa}
Ce	60 ppm ^a	Ge	1.4 ppm ^m	Os	0.05 ppb ^{bb}
Ni	56 ppm ^a	Eu	1.3 ppm ^a	Ir	0.05 ppb ^{aa}
La	30 ppm ^a	Ta	1.1 ppm ⁿ		

UC = Upper Crust, LC = Lower Crust

- a UC: SHAW et al. (1967, 1976), LC: RUDNICK and PRESPEL (1990) in the proportions of Fig 2
- b Fig. 7
- c UC: calculated from rock averages compiled by PUCHELT (1972) in the proportions of Fig. 2, LC: RUDNICK and PRESPEL (1990)
- d UC: calculated from rock averages compiled by WEDEPOHL (1987) in the proportions of Fig. 2, LC: averages of granulites and gabbro
- e UC, LC: calculated from rock averages compiled by WLOTZKA (1972) in the proportions of Fig. 2 (additional data on granites HALL, 1988)
- f UC: calculated from rock averages compiled by HARDER (1974) and SHAW et al. (1986) in the proportions of Fig. 2, LC: data from TRUSCOTT et al. (1986), LEEMAN et al. (1992) and HARDER (1974)
- g interpolated from smooth curve of chondrite normalized REE distribution in the continental crust
- h UC: Rb/19 according to MCDONOUGH et al. (1992), LC: RUDNICK and PRESPEL (1990)
- i UC: calculated from rock averages compiled by HOERMANN (1969) in the proportions of Fig. 2, LC: SIGHINOLFI (1973)
- k UC: calculated from rock averages compiled by HAMAGUCHI and KURDODA (1969) and SMITH and BURTON (1972) in the proportions of Fig. 2, LC: RUDNICK andd PRESPEL (1990)

Table 2. (Continued)

l	UC: calculated from rock averages of ONISHI and SANDELL (1955), BURWASH and CULBERT (1979) in the proportions of Fig. 2, LC: gabbro, gneiss minus 20% granite
m	UC: calculated from rock averages compiled by HOERMANN (1970) and ONISHI (1956) in the proportions of Fig. 2, LC: gneiss, gabbro
n	UC: calculated from Nb/Ta = 17.5 (from international reference rocks) GLADNEY et al. (1983), LC: RUDNICK and PRESPPER (1990)
o	UC: calculated from rock averages compiled by MANHEIM and LANDERGREN (1978) in the proportions of Fig. 2, gabbro, gneiss minus 20% granite
p	UC, LC: calculated from rock averages compiled by FUGE (1974a) (partly corrected with Cl/Br ratio 1000) in the proportions of Fig. 2. Sedimentary rocks calculated with Cl/Br = 290 (seawater)
q	UC, LC: calculated from rock averages compiled by KRAUSKOPF (1970) in the proportions of Fig. 2
r	UC: calculated from rock averages compiled by FUGE (1974b) and BECKER et al. (1972) in the proportions of Fig. 2 considering accumulation in C _{org} rich sediments (C/I correlation of PRICE et al. 1970), LC: estimated
s	UC, LC: calculated from rock averages of HEINRICHS et al. (1980) in the proportions of Fig. 2
t	UC: calculated from rock averages of ONISHI and SANDELL (1955) and BURWASH and CULBERT (1979) in the proportions of Fig. 2, LC: estimated
u	UC, LC: calculated from rock averages of KOLJONEN (1973) and KELTSCH (1983) in the proportions of Fig. 2, S/Se in crustal rocks except sediments: 8.5×10^3
v	UC, LC: calculated from rock averages of HAMAGUCHI and KURODA, (1959) in the proportions of Fig. 2, Cu/Ag in felsic rocks 300 to 450
w	UC, LC: calculated from rock averages compiled by LINN and SCHMITT (1972) and contributed by VOLAND (1969) in the proportions of Fig. 2
x	UC, LC: calculated from rock averages compiled by the present author partly from MAROWSKI and WEDEPOHL (1971) and partly from unpublished data of HEINRICHS in the proportions of Fig. 2
y	UC, LC: order of magnitude estimated from data on international reference rocks (GLADNEY et al., 1983, SIGHINOLFI et al. 1979) and on MORB (HERTOGEN et al. 1990)
z	UC: calculated from rock averages compiled by CROCKET (1974) in the proportions of Fig. 2, LC partly from SIGHINOLFI and SANTOS (1976) partly from gabbro
aa	UC, LC: from composite sample of 17 European greywackes analysed by ICP MASS in nickel sulfide extract after Te coprecipitation (HARTMANN, 1995)
bb	UC: ESSER and TUREKIAN (1993)

from Heinrichs et al. (1980). They calculated upper crust averages of Li, Be, B, Ge, As, Se, Zr, Mo, Ag, In, Sb, Ba, W, and Re from the respective compilations edited by Wedepohl (1969–1978). The former authors obtained a granodioritic bulk composition for the upper continental crust. Large sets of sedimentary rock samples from geosynclines and platforms have been analysed by Ronov and Yaroshevskiy (1968) to get an average composition of the sedimentary top of the crust. This has especially accumulated some rather mobile compounds, partly of volatile elements (CaCO₃, NaCl, etc). A comprehensive compilation of chemical data on granulites as the most abundant lower crustal rocks has been published by Rudnick and Presper (1990).

A distinct discrepancy in estimates about the size and composition and in assumptions about the genesis of the lower and the bulk crust exists between the widely used report of Taylor and McLennan (1985) and the results of our present investigation. These authors assume that the lower crust comprises 75% of the total crust in contrast to our above listed 50% estimate based on the EGT seismic profile through Europe. Taylor and McLennan (1985) calculated the average

lower crust composition by removal of their upper from their bulk crust composition. They got a lower crust which is distinctly more mafic (54.4% SiO₂) than average diorite or andesite (57.7% SiO₂; Le Maitre, 1976). The former authors modelled a dioritic continental crust from their Archean crust composition (75%) and from island arc andesites (25%). Their Archean crust consists of a 2:1 mixture of mafic (MORB) and felsic (tonalitic to trondhjemitic) endmembers, which is in REE composition conformable with andesites (or diorites). The model proposed by Taylor and McLennan (1985) obviously overestimates the abundances of andesites and diorites at active continental margins and in the bulk crust. These authors stated that their model is constrained by the assumption of about 40% of the total heat flow at the average Earth's surface being derived from the crust and 60% from the mantle. They have calculated that for the respective heat production a bulk crust abundance of 9000 ppm K, 3.4 ppm Th and 0.9 ppm U is required. Information from refraction seismic profiles on the crustal structure and composition is expected to be more reliable than crustal models based on heat production of the silicate earth.

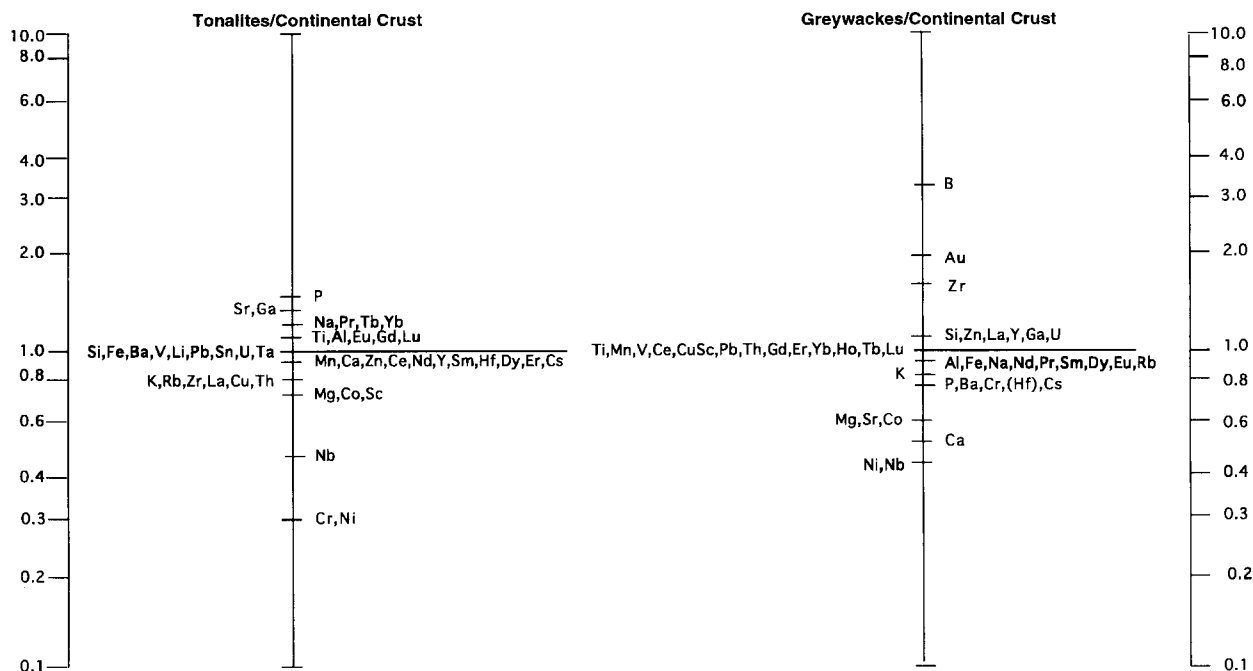


FIG. 3. Average composition of tonalites and greywackes from worldwide sampling (Table 3) in comparison with the composition of the continental crust.

CRUSTAL CONCENTRATIONS OF MAJOR ELEMENTS AND COMMONLY ANALYSED MINOR ELEMENTS

We have recalculated the composition of the continental crust in the proportions of upper crust to lower felsic crust to lower mafic crust being equal to about 1:0.6:0.4 as derived from the EGT refraction seismic profile through Europe. The precise proportion of these units and of additional subunits in a standard crustal profile is listed in Fig. 2. The abundance of major sedimentary, magmatic, and metamorphic rocks in the subunits of the continental crust is derived from the evaluation of mapping and drilling reports (mainly from Ronov and Yaroshevskiy, 1968; Daly, 1933; Moore, 1959; supplemented by additional authors). The chemical composition of the upper and the lower continental crust is for the majority of commonly analysed elements taken from Shaw et al. (1976, 1986) and from Rudnick and Presper (1990), respectively. The latter authors presented averages of Archean and post-Archean felsic granulites from terrains (which we used in a proportion of 1:1) and of mafic granulites sampled as xenoliths. Our data for the upper and lower continental crust and for the bulk continental crust are presented in Tables 1 and 2, respectively. These tables also contain data on additional elements which were not considered in the above-mentioned references. They will be handled in the next section. Our bulk crust has a tonalitic composition (cf. Fig. 3) and is also close to the average of felsic granulites of Rudnick and Presper (1990) and not much different (except Fe and Ta) from the felsic granulites of Shaw et al. (1986). The continental crust calculated by us (Tables 1 and 2) has about twice the concentration of heat producing elements of the crustal model suggested by Taylor and McLennan (1985).

There exists ample experimental evidence (Rushmer, 1991; Wolf and Wyllie, 1991; Springer and Seck, 1995; Rapp, 1994) that tonalites are partial melting products of mafic rocks under water-undersaturated conditions. This suggests that a part of the felsic lower crust has formed from tonalitic partial melts derived from the mafic lower crust after supply of water from mafic intrusions and dehydration of subducted ocean crust. This water might have introduced a certain fraction of K and other incompatible elements into the volume of partial melting. A part of the felsic lower crust is residual from the formation of granitic partial melts during orogenic heating. We have calculated the composition of a felsic lower crust fragment after subtraction of 30% granitic partial melt (1:1 mixture of I- and S-type felsic granulites of Whalen et al., 1987). The residuum has a major element composition close to diorites as listed in Table 4. The minor elements Sc, Cr, Co, Ni, and HREEs increased and Rb, Cs, Pb, Th, and U decreased in the residuum relative to the felsic lower crust after granitic melt separation. The minor dioritic residuum stays in the predominantly tonalitic substratum of the felsic lower crust, which preserves its overall tonalitic composition.

Greywackes approach on average the chemical composition of tonalites with the exception of B, Zr, Si, Ca, P, and Cr (Table 3, Fig. 3). This characterizes them as major products of erosion at active continental margins and indicates the importance of tonalites as early products of magmatism generating new continental crust at plate boundaries. The average metamorphic rocks of the continental upper crust (64% gneiss, 15% mica schist, 18% amphibolite; cf. Fig. 2) and especially their major proportion of gneisses are close in chemical composition to tonalites and greywackes, the latter

with the exception of SiO_2 . The chemical connection indicates genetic relationship.

A critical proof of the representativeness of the Canadian Shield major element data for the composition of the upper continental crust is presented in Table 5. In this table chemical compositions of major subunits of the upper continental crust are summed up with the statistical weight of their abundance as listed in Fig. 2. The sum of the subunits in Column H is compared with the Canadian Shield data of Shaw et al. (1976). There exists a good correspondence between the two sets of data with a little more than 10% deviation in SiO_2 , TiO_2 , Fe_2O_3 , and Na_2O . The deviation in Na_2O decreases but does not disappear if the seawater reservoir of this element is considered. The deviation in SiO_2 might be caused by the mobility of this compound in hot water and its accumulation in quartz veins. Some other minor deviations could depend on our choice of data for rock units in Table 5. The good correspondence has encouraged us to use the Canadian Shield as representative of the upper continental crust. It additionally suggests to employ the rock abundances of Fig. 2 as statistical weight for the calculation of minor element abundances not considered in the investigations by Shaw et al. (1967, 1976, 1986) in a later section.

After a critical proof of the major set of data on the upper crust we have to test the reliability of our assumptions on the bulk crust. For this test we use the experience about the crustal and bulk earth distribution of several radioactive and radiogenic isotopes. Some elements which have important radioactive/radiogenic isotopes are connected by close crystal chemical relations. Rb, Th, U, K, and Pb are highly incompatible in mantle minerals and therefore extremely accumulated in the continental crust relative to the primitive mantle (factor hundred; cf. Fig. 5). Pairs of element abundances in the continental crust, which are neighbors or almost neighbors in the sequence of incompatibility of Fig. 5 form element ratios in which they do not differ much from the respective primitive mantle (PM) ratios, the latter as reported by Hofmann (1988). The Th/U ratio is 5 in the calculated crust and 4 in the PM. The more incompatible Th being more enriched in the crust. Asmerom and Jacobsen (1993) have calculated an average Th/U ratio of 4.1 from the lead isotopic composition of suspended river loads with a Nd model age from 0.5–3.5 Ga. This result although conformable with our Th/U ratio of the upper crust (Table 1) might suggest a slightly smaller ratio than 5 for the bulk crust. Our K/U ratio is 1.26×10^4 for the bulk crust compared with 1.27×10^4 in the PM. The U/Pb and K/Pb ratios are 0.115 and 1445 in the crust and 0.116 and 1475 in the PM, respectively. The K/Rb ratio is 274 in the crust and 482 in the PM with the less mantle compatible Rb being more enriched in the crust. The Rb/Sr and U/Pb systems important for the crust are interconnected by the K/Rb and K/U relations. The crustal behavior of Rb, Pb, Tl, and several other elements is controlled by their crystal chemical connection to K and their affinity to the feldspar and mica structures. Minor differences in this behavior between Rb, Pb, and Tl are reflected in the different slopes of element distributions in major rock types plotted in Fig. 6.

The link between the Rb/Sr and Sm/Nd systems is the comparable mantle incompatibility of Sr and Nd (Fig. 5). The

Sr/Nd ratios for the continental crust and the PM are 12.3 and 15.3 with the slightly more compatible Sr causing the lower crustal ratio. We have used the element or isotope ratios of worldwide river loads to check our calculated bulk crust (Table 2) and upper crust (Table 1) element ratios (Fig. 4). Erosion has apparently favoured the upper crust slightly more than the lower crust as reflected in the Rb/Sr and U/Pb systems. In a plot of chondrite normalized REE concentrations the elements with high analytical precision give a smooth curve. We have corrected the REEs with lower analytical precision and have estimated the Pr, Dy, Er, and Tm concentrations, which were not analysed in the Canadian Shield, by interpolation in that curve. The final values are presented in Table 2. Our crustal Lu/Hf ratio is the same as that reported by Patchett et al. (1984) for common sedimentary rocks (except pelagic deposits) and used for their isotope studies.

The check by isotope constraints suggests that the use of the data by Shaw et al. (1967, 1976) on the upper crust and those by Rudnick and Presper (1990) on the lower crust in the proportions derived from the EGT profile is recommended for a calculation of the bulk crust composition.

CRUSTAL CONCENTRATIONS OF RARELY ANALYSED ELEMENTS

Table 2 contains major element and thirty-two minor element data from our investigation in the former section. The gaps in Table 2 to be filled in this section concern thirty-three additional minor elements. For two of them (Ba, Ta) Shaw et al. (1967, 1976) and Taylor and McLennan (1985) report very different concentrations (1070 and 550 ppm Ba, 5.7 and 2.2 ppm Ta, respectively) for the upper crust. The average Ba concentrations analysed in the Canadian Shield are even different between Shaw et al. (1967, 1976) and Eade and Fahrig (1971) (1070 and 810 ppm Ba). If we use the rock abundances listed in Table 2 and Ba averages for common rock species as reported by Puchelt (1972) we get an upper crust value of 668 ppm Ba which is intermediate between the upper crust value of Taylor and McLennan (1985) and the Canadian Shield concentration of Eade and Fahrig (1971). Our Ba/U (344) and Ba/Th (68.7) ratios are slightly higher and lower than the respective PM ratios (298, 74.4; Hofmann, 1988), which indicates that either the mantle incompatibility of Ba has to be positioned (in deviation from Fig. 5) between Th and U or that the crustal abundance of Ba could be slightly higher. In every case should the crustal Ba/Rb ratio be lower than the PM ratio of 11.3. It could be a little higher than our present value of 7.5. If we calculate the Ta concentration in the upper crust from the Nb concentration by the use of the PM ratio of 17.6 (Hofmann, 1988) the value of 1.5 is still slightly lower than 2.2 ppm Ta reported by Taylor and McLennan (1985). Our calculation is supported by the fact that analytically very precise data on seven standard reference rocks (granites, basalts, andesite) compiled by Gladney et al. (1983) have on average a Nb/Ta ratio of 17.7. Older data on common rocks as those compiled by Wedepohl (1978) give lower Nb/Ta ratios closer to 10 than to 17.6. This is probably an analytical problem.

For two of the rather abundant minor elements (C and S), for which we have not many reliable data on magmatic and

Table 3 Average concentration of elements in tonalites and greywackes from worldwide sampling in comparison with the Continental Crust

	A Continental crust	B Tonalites	C Greywackes	B/A	C/A
SiO₂	61.5%	61.9 %	69.1%	1.00	1.12
TiO₂	0.68	0.77	0.72	1.13	1.06
Al₂O₃	15.1	16.3	13.5	1.07	0.89
Fe₂O₃	6.28	6.3	5.9	1.00	0.94
MnO	0.10	0.09	0.10	0.90	1.00
MgO	3.7	2.6	2.3	0.70	0.62
CaO	5.5	4.9	2.6	0.89	0.47
Na₂O	3.2	3.9	3.0	1.22	0.94
K₂O	2.4	1.9	2.0	0.79	0.83
P₂O₅	0.18	0.26	0.13	1.44	0.72
Ba	584 ppm	608 ppm	426 ppm	1.04	0.73
Sr	333	439	201	1.32	0.60
Zr	203	173	302	0.85	1.49
Cr	126	38	88	0.30	0.70
V	98	103	98	1.06	1.00
Rb	78	64	72	0.82	0.92
Zn	65	61	76	0.94	1.16
Ce	60	53	58	0.89	0.96
Ni	56	19	24	0.34	0.43
La	30	23	34	0.77	1.13
Nd	27	25	25	0.93	0.93
Cu	25	19	24	0.76	0.98
Co	24	16	15	0.67	0.63
Y	24	22	26	0.93	1.08
Nb	19	8.8	8.4	0.46	0.44
Li	18	19	-	1.06	-
Sc	16	11	16	0.67	1.00
Ga	15	19	16	1.30	1.08
Pb	14.8	14.2	14.2	0.95	0.95
B	11	-	37	-	3.3
Th	8.5	6.4	9.0	0.76	1.06
Pr	6.7	8.5	6.1	1.27	0.91
Sm	5.3	4.9	4.6	0.92	0.86
Hf	4.9	4.6	3.5	0.93	0.71
Gd	4.0	4.2	4.0	1.05	1.00
Dy	3.8	3.5	3.4	0.92	0.90
Cs	3.4	3.2	2.2	0.93	0.65
Sn	2.3	2.4	-	1.04	-
Er	2.1	1.9	2.2	0.90	1.02
Yb	2.0	2.4	2.1	1.20	1.05
U	1.7	1.7	2.0	1.00	1.16
Eu	1.3	1.4	1.2	1.06	0.88
Ta	1.1	1.1	-	1.00	-
Ho	800 ppb	900 ppb	780 ppb	1.11	0.98
Tb	650	750	630	1.15	0.96
Lu	350	370	370	1.06	1.06
Au	2.5	-	4.8	-	-
Pd	0.4	-	0.4	-	-
Pt	0.4	-	0.4	-	-
Ru	0.1	-	0.1	-	-

Table 3 (continued)

	A Continental crust	B Tonalites	C Greywackes	B/A	C/A
Rh	0.06	-	0.06	-	-
Ir	0.05	-	0.05	-	-

Tonalites: Total average of group averages from USA, Canada, Sri Lanka, Greenland, Finland, UK, Portugal, with equal statistical weight: ARTH et al. (1978), ERMANOVICS et al. (1979), TARNEY et al. (1979), SCHERMERHORN (1987 and person. comm.), PARADIS et al. (1988), POHL and EMMERMANN (1991), WEDEPOHL et al. (1991), TEPPER et al. (1993)

Greywackes: Total average of group averages from USA, Canada, Australia, India, Sri Lanka, Germany with equal statistical weight: WEBER (1960), ONDRICK and GRIFFITHS (1969), TAYLOR and McLENNAN (1985), POHL and EMMERMANN (1991), WEDEPOHL (composite 17 greywackes, Germany, unpubl.)

metamorphic rocks, we have provided a stable isotope balance to improve the bulk crust abundance values (Fig. 7). These elements occur mainly in two valence states (with very different isotopic characteristics) and are highly accumulated in the sedimentary top of the crust. The bulk crust isotope data of the two balances must be close to the most probable values for the mantle. The carbon balances suggest that the proportion of carbonate rocks in the sedimentary column as calculated by Ronov and Yaroshevskiy (1968), has to be reduced from 17.6 to 14.6%. The sulfur balance suggests a value for the abundance of SO₄ in evaporites. This value is very important for an evaluation of the crustal distribution of Cl. The high mobility of NaCl, its abundance in common sedimentary rocks and the scarcity of data on chlorine in magmatic and metamorphic rocks are some of the difficulties for the calculation of a reliable value of the Cl abundance in the continental crust which we have investigated in detail (Wedepohl, 1987). This element is highly accumulated in the sedimentary top of

the crust (55%) whereas F occurs mainly in the magmatic and metamorphic part of the crust where it replaces OH in mineral structures. The other elements which are especially accumulated in the sedimentary cover are I, Br, B, Hg, N, and As which form mobile and/or volatile compounds (Fig. 8).

The crustal abundances in Table 2, which were not reported in the former section, are all calculated from literature data (foot-notes in Table 2) on common rocks with the statistical weight of the rock abundances in the upper and lower crust respectively (Fig. 2). For some of the elements (Be, Ge, Mo, I, Sb, In, Te, Pt-group, and Re) reliable literature data on common rocks, especially on metamorphic rocks, are rather rare. Sample contamination is a serious problem with several of the rare elements (I, Hg, Pt-group, etc.). Knowledge about the crystal chemical behavior of some rare elements allows a separate check on their crustal abundance. In common rocks the following element ratios are almost constant: Si/Ge and Si/Sn ~ 10⁵, S/Se ~ 10⁴, As/Sb ~ 6, Cl/Br ~ 300 (sedi-

Table 4 Balance of residual rocks after 30% partial melting of felsic lower crust

	A Felsic lower crust	B Granites (I and S felsic)	C Felsic lower crust minus 30% B	D Diorites
SiO₂	63.1	73.4	58.7	57.5
TiO₂	0.70	0.27	0.88	0.95
Al₂O₃	14.86	13.5	15.4	16.7
Fe₂O₃	6.89	2.0	8.9	8.0
MnO	0.10	0.04	0.12	0.12
MgO	3.60	0.57	4.9	3.7
CaO	4.83	1.50	6.3	6.6
Na₂O	3.17	3.10	3.9	3.5
K₂O	2.11	4.35	1.2	1.8
P₂O₅	0.18	0.10	0.21	0.29

Reference: RUDNICK and PRESPEL (1990)

WHALEN et al. (1987)

LE MAITRE (1976)

Table 5 Balance of major rock species in the Upper Continental Crust

	A	B	C	D	E	F	G	
	Sedimentary rocks (proport. acc. Fig. 2)	Granites (I and S felsic)	Granodiorites	Tonalites	Gabbros	Metamorphic Rocks (proport. acc. Fig. 2)	Upper continental crust (Canad. Shield)	15 % A, 25% B, 20% C, 4% D, 6% E, 30% F
SiO ₂	52.4	73.4	66.1	61.9	50.1	63.7	64.9	64.0
TiO ₂	0.68	0.27	0.54	0.77	1.10	0.74	0.52	0.59
Al ₂ O ₃	13.7	13.5	15.7	16.3	15.5	15.1	14.6	14.7
Fe ₂ O ₃	6.4	2.0	4.4	6.3	11.5	5.96	4.4	4.9
MnO	0.12	0.04	0.08	0.10	0.12	0.10	0.07	0.08
MgO	3.3	0.57	1.74	2.6	7.6	2.91	2.2	2.4
CaO	9.0*	1.50	3.83	4.9	4.58	3.88	4.1	4.1
Na ₂ O	1.65	3.10	3.75	3.9	2.4	2.87	3.5	2.9/3.1**
K ₂ O	2.14	4.35	2.73	1.9	0.9	3.21	3.1	3.1
P ₂ O ₅	0.18	0.10	0.18	0.26	0.24	0.22	0.15	0.17
H ₂ O ⁺	3.1	0.6	0.8	0.7	0.7	0.5	0.8	1.0
CO ₂	5.9*					1.1		0.80
Reference	RONOV and YAROSHEVSKIY (1968) *corrected acc. Fig. 7	WHALEN et al. (1987)	LEMAITRE (1976)	Table 3	LEMAITRE (1976)	POLDERVAART (1955)	SHAW et al. (1967, 1976)	Fig. 2 ** including oceans

ments exclusively), $K/Tl \sim 4 \times 10^4$ (cf. Fig. 6), $K/Bi \sim 2.5 \times 10^5$, $Rb/Cs = 19$ (except felsic lower crust; McDonough et al., 1992), $Cu/Ag \sim 4 \times 10^2$ (except mafic rocks), $Cu/Au \sim 6 \times 10^3$ (except mafic rocks). The sequence of abundances of Pt-group elements in primitive ultramafic rocks is controlled by their cosmic abundance and the occurrence of sulfides: $Pt > Ru > Pd > Ir \sim Os > Rh$. Under the redox conditions in the crust being different from those of the PM the sequence changes to $Pd \sim Pt > Ru > Rh \geq Os, Ir$. The element Mo being almost as compatible as Pr is expected to have a crustal Mo/Pr ratio close to that of the PM (0.23; Newsom et al., 1986). Our ratio of 0.16 from Table 2 indicates that Mo is slightly less incompatible at partial melting in the

mantle than Pr. The correct order of magnitude confirms the base of our calculated Mo abundance.

GENETIC IMPLICATIONS

The explanation of the formation of the continental crust has to proceed from the fact that it consists mainly of tonalites and to a minor degree of granites, granodiorites, and mafic rocks. The primary magmas for its genesis were mafic partial melts from the upper mantle. The concentrations of highly incompatible elements in the crust exceed those of the primitive mantle by a factor of hundred (Fig. 5). MORB magmas as the most abundant partial melts from the present upper

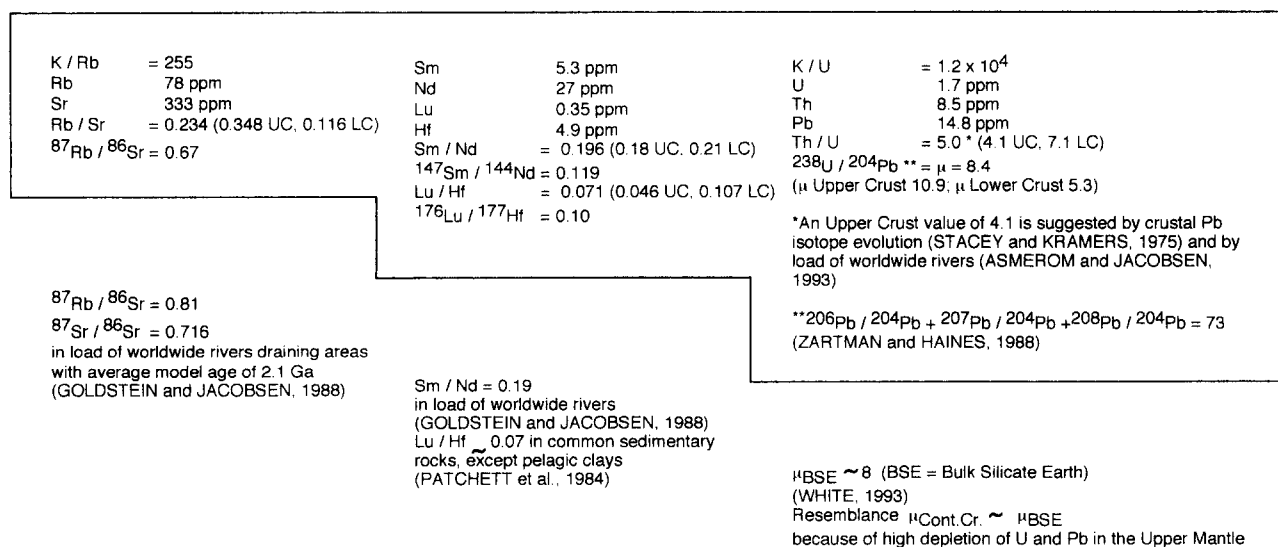


FIG. 4. Average composition of the continental crust in elements with important radioactive and radiogenic isotopes. Comparison with worldwide river loads.

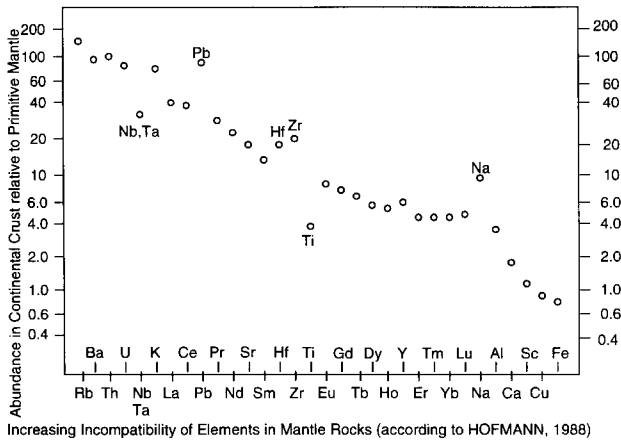


FIG. 5. Average composition of the continental crust in selected elements normalized to the primitive mantle (acc. to Hofmann, 1988). The elements are plotted in the sequence of increasing compatibility.

mantle are characterized by a large depletion of these highly incompatible elements which is complimentary to their accumulation in the crust (Hofmann, 1988).

Extensive partial melting in a subducted fraction of the early mafic crust which was caused by the relatively high heat

production of the early upper mantle has probably formed the primordial felsic cores of the continents (McCulloch, 1993). At increasing thickness of the continental crust this process of formation of tonalitic partial melts shifted into the mafic lower crust and was controlled by water from mafic intrusions and dehydration of subducted ocean crust. A certain thickness of the tonalitic crust and heat advection has allowed its partial melting to form granitic magmas. Melt separation and uprise of felsic magmas from their source was the major process of chemical fractionation within the continental crust. Additional fractionation was caused by weathering and selective water transport of the weathering products to form greywackes, clays, sands, carbonates, and evaporites. Camiré et al. (1993) have calculated that Archean greywackes from the Canadian Shield are derived from about 65% tonalites/trondhjemites, 30% tholeiitic basalts, and 5% komatiites which is almost identical with the lower crust composition derived by us (Fig. 2).

The almost smooth curve of primitive mantle normalized element concentrations of Fig. 5 is based on a certain sequence of increasing compatibility of elements in the structure of common mantle minerals. This was derived by Hofmann (1988) and Sun et al. (1979) from element behavior at MORB formation. The smooth part of the curve of Fig. 5 reflects partial melting of upper mantle rocks as the major

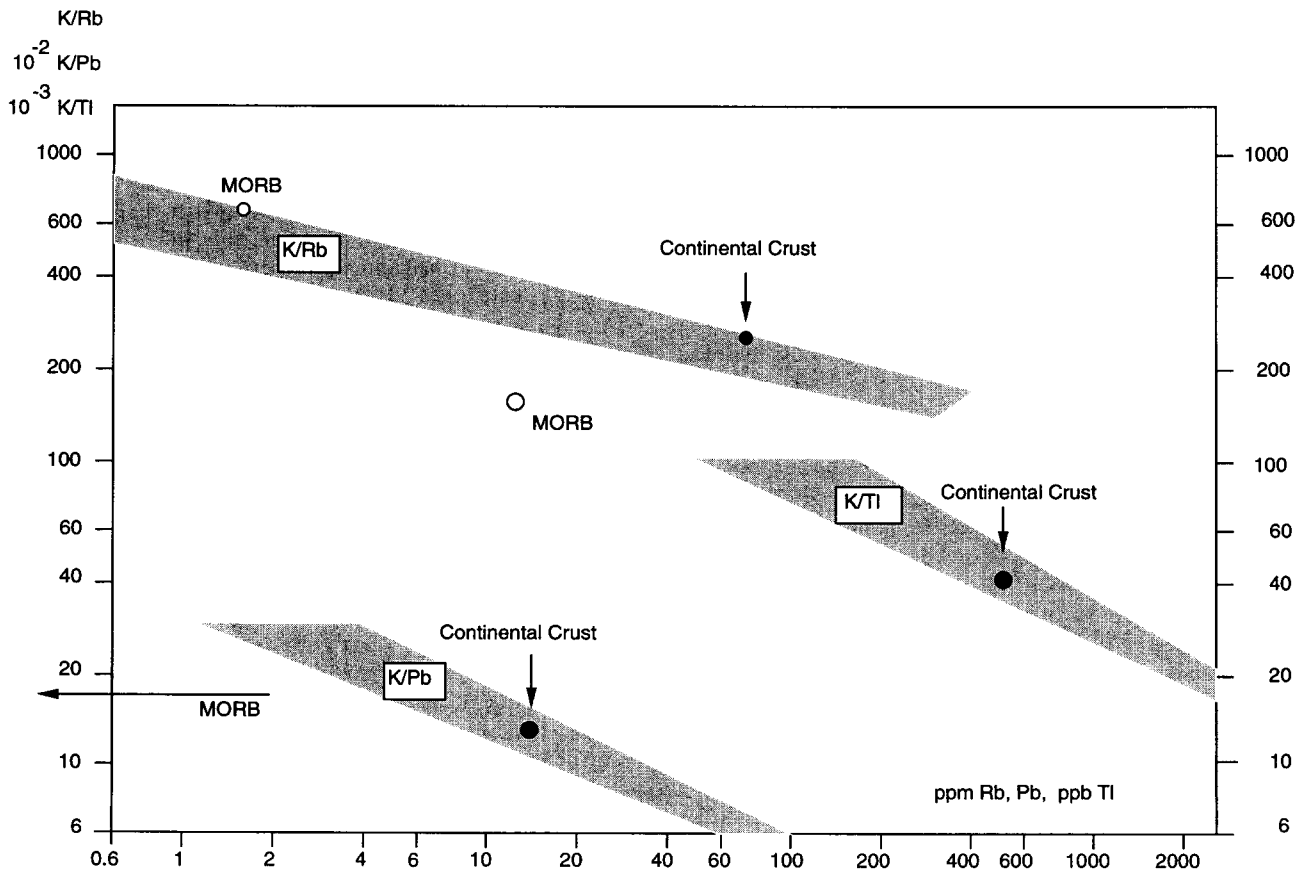


FIG. 6. Correlation of K/Rb, K/Pb and K/Tl ratios with Rb, Pb and Tl concentrations in abundant crustal rocks (data from Heinrichs et al. 1980, MORB data on K, Rb, Pb from Hofmann, 1988).

Carbon				Sulfur					
		ppm C *	Mass Proportion	$\delta^{13}\text{C} \text{‰}^*$		ppm S ∇	Mass Proportion	$\delta^{34}\text{S} \text{‰}^{\nabla}$	
7.4 %	Sediment. R.: Carbonates	16000**	79.7%	0	7.4 %	Sedimentary Rocks:			
	Reduced Carbon	4000***		-25		(Excluding Evaporites)	2860		-15
26.5 %	Felsic Intrusives	360	5.1%	-15		Including Evaporites	3810	42.3 %	-6.7
3.2 %	Gabbros	220	0.4%		26.5 %	Felsic Intrusives	334	13.3 %	+1.4
15.9 %	Gneisses, Schists, etc.	820	7.0%	-13	3.2 %	Gabbros	780	3.5 %	+0.5
28.9 %	Felsic Granulites	820	5.6%	-13	15.9 %	Gneisses, Schists, etc.	690	16.2 %	+3.0
18.1 %	Mafic Granulites	220	2.2%			Upper Continental Crust	953	75.3 %	-2.8
	Continental Crust	1990	(4.2x10 ¹⁶ t C)	-6 ‰****		28.9 % Felsic Granulites	350	11.1 %	+3.0
						18.1 % Mafic Granulites	500	13.6 %	+0.5
						Lower Continental Crust	408	24.7 %	+1.8
						Continental Crust	697	(1.44x10 ¹⁶ t S)	-1.66 $\nabla\nabla$

* Abundances mainly from HOEFS (1973), SCHWARCZ (1969), VEIZER and HOEFS (1976), JUNGE et al. (1975), HOEFS (1969)

** Abundance of Sedimentary Carbonates reported by RONOVS and YAROSHEVSKIY (1968) reduced from 22500 to 16000 ppm C to adjust the proportion of Carbonate to Reduced Carbon to 4 : 1

*** RONOVS (1958)

**** The Mantle Source is often reported to contain $\delta^{13}\text{C}$ from -5 to -6 ‰

∇ Abundances mainly from RONOVS et al. (1974), RONOVS and YAROSHEVSKIY (1968), KAPLAN et al. (1963), SIEWERS (1974), SCHNEIDER (1978), WEDEPOHL (1987), WEDEPOHL et al. (1991)

$\nabla\nabla$ Crustal Sulfur must be supplemented by Seawater Sulfur (1.4 x 10¹⁵ t S; $\delta^{34}\text{S} + 20 \text{‰}$) to get $\delta^{34}\text{S} + 0.3 \text{‰}$ (Mantle Source, not far from Meteoritic Troilite)

FIG. 7. Balances of C and S and their isotopic composition in the continental earth's crust.

process of incompatible element accumulation in the crust. A few deviations from this character can be used to identify additional processes partly connected with the formation of tonalites. The large accumulation of Rb, Ba, K (and Cs) in the continental crust indicates that residual K-feldspar, mica (and amphibole) were unimportant at the formation of tonalitic magmas.

We explain the required shift of Nb, Ta, and Ti in Fig. 5 to positions of larger compatibility in the curve of element distribution to balance the depletion as due to the existence of residual rutile at the formation of tonalitic partial melts (Rapp, 1994). The excess of Zr and Hf was caused by the temperature dependent extraction of these elements by the tonalitic melts from their mafic source. An average concentration of 200 ppm Zr in the continental crust indicates temperatures of partial melting not far from 850°C. (Watson and Harrison, 1983). The excess of Pb in the continental crust was explained by Peucker-Ehrenbrink et al. (1994) as due to the hydrothermal leaching of the ocean crust and remobilization of leached Pb at the dehydration of subducted ocean crust into continental magma.

The formation and chemical fractionation of the continental crust required water. By far the largest amount of crustal water occurs in the oceans ($1.4 \times 10^{18} \text{t}$) and the second largest fraction in the porous volume of sediments ($0.3 \times 10^{18} \text{t}$). The continental crust (excluding the oceans) contains on average about 2% H₂O which is mainly accumulated in the upper crust and its sedimentary top. Dehydration of subducted ocean crust and of hydroxide containing minerals in the continental crust is required for partial melting in the mafic and

felsic lower crust, respectively. Mantle degassing has formed the atmosphere and the hydrosphere and has controlled weathering at the Earth's surface as well as the accumulation of C, S, Cl, N, Ar, B, As, Br, I, Sb, Se, and Hg.

The compositions of the upper and lower continental crust are compared in Fig. 8. The elements which form volatile compounds and the highly incompatible elements characterize the upper crust and 3-d elements are specifically accumulated in the lower crust. This fractionation is mainly caused by the uprise of granitic melts and the preferential intrusion of tholeiitic basaltic magmas into the lower crust due to their compressibility (Kushiro, 1982). Both processes are interrelated.

The standard crustal profile of Fig. 2 which was derived from the European Geotraverse is converted into a cartoon with symbolized compositions and processes (Fig. 9). Rock species are drawn almost in their correct proportions with felsic rocks in white and mafic rocks in black. By far the largest proportion of felsic rocks has a tonalitic composition. It is formed in the mafic lower crust and intrudes into the upper together with granitic magmas at orogenic events (Pitcher, 1979). Granitic partial melts from a tonalitic or sedimentary source have increased in their proportion of the crustal magmatic production during Earth's history. Crustal temperatures as calculated by Chapman (1986) are listed in the left part of Fig. 9. In our test area of the EGT, the heat flow density increases from the Scandinavian Shield (40 mW m⁻²) through Central Europe (60 mW m⁻²) to the Alpine orogen ($\leq 90 \text{ mW m}^{-2}$; for details of the Moho temperature see Banda and Cloetingh, 1992). Orogenic heating which is re-

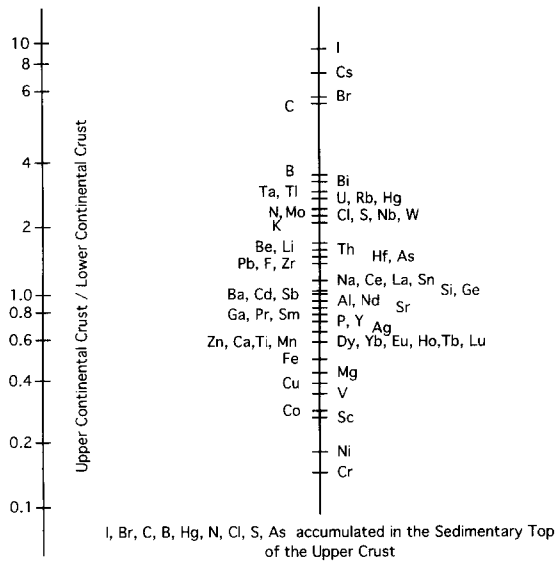


FIG. 8. Comparison of the average composition of the upper with the lower continental crust (Table 1; references in footnotes of Table 2).

quired for partial melting within the crust was mainly caused by mafic intrusions. At a heat flow density of 90 mW m^{-2} the temperature at Moho depth is more than 1000°C which allows water undersaturated partial melting of mafic rocks. The for-

mation of water undersaturated granitic melts from abundant source rocks requires about 800°C (Johannes and Holtz, 1990).

In the shield areas with their larger thickness and distinctly lower temperatures mafic granulites can be converted into eclogites (Ringwood, 1975). This material with a density higher than that of lherzolite can sink into the mantle if tectonically separated from the lower crust. This process of delamination, which will exclude very dense upper mantle, is required to recycle the major part of the mafic lower crust back into the mantle. The different stages of the mafic lower crust which was formed during Earth's history must have been in total much thicker than the present lowest part of the crust (average 7 km). One single intrusion such as that of the Ivrea area in northern Italy has about 10 km thickness. A bulk crust with about 30 km tonalite required 90 to 120 km mafic source rocks if their degree of partial melting was 25 to 30%. An open-system behavior of the crust, which was caused by a major delamination of eclogite with excess Eu^{2+} , is indicated by the depletion of Eu^{2+} in the majority of crustal rocks. The lower crust contains on average a surplus of 0.2 ppm Eu^{2+} (based on data reported by Rudnick and Presper, 1990) and the upper crust has a deficit of 0.58 ppm Eu^{2+} (based on data compiled by Wedepohl, 1991, and calculated in the rock proportions of Table 5, last column). This comparison clearly demonstrates the major depletion of Eu^{2+} in the bulk continental crust. The result agrees with data from a bulk crust section in China (Gao et al., 1992).

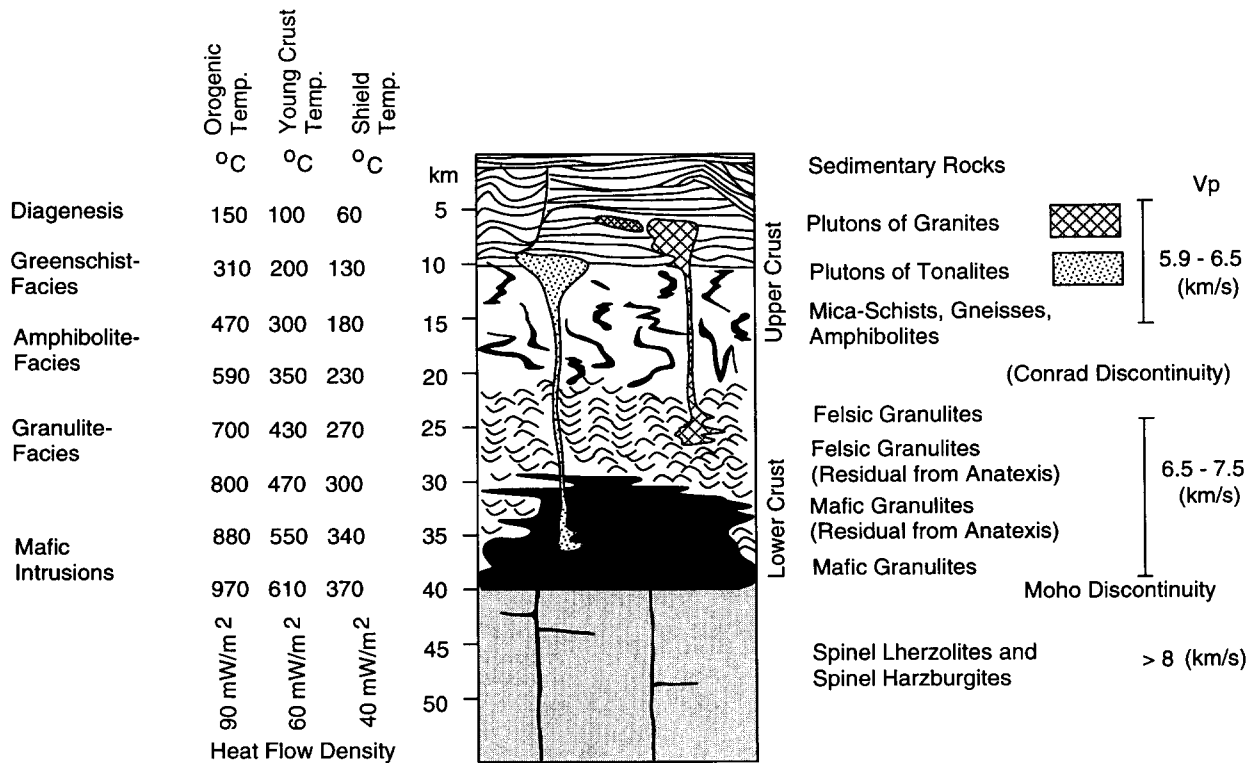


FIG. 9. Cartoon of the standard profile of the continental crust with temperature-depth relations of 3 geotherms calculated by Chapman (1986).

The crustal composition as calculated in this investigation is distinctly more felsic than that modelled by Taylor and McLennan (1985). The amount of the most incompatible elements in the continental crust cannot have been supplied from the primitive composition of the upper convecting mantle with 670 km depth exclusively. More than half of the crustal reservoir of Cs, Rb, and Ba and half of that of Th, U, and K must originate from the lower mantle. The separation of the convection cells of the upper and lower mantle was apparently interrupted during certain episodes which requires future investigations.

Our results on the crustal composition have mainly benefited from recent research on the lower continental crust. Constructive discussions with numerous colleagues and assistance in the graphical presentation of the results were gratefully accepted.

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