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EuCRUST-07: A new reference model for the European crust

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[1] We present a new digital model (EuCRUST-07) for the crust of Western and Central Europe and surroundings (35°N–71°N, 25°W–35°E). Available results of seismic reflection, refraction and receiver functions studies are assembled in an integrated model at a uniform grid ($15' \times 15'$). The model consists of three layers: sediments and two layers of the crystalline crust. Besides depth to the boundaries, we provide average *P*-wave velocities in the upper and lower parts of the crystalline crust. The new model demonstrates large differences in the Moho depth compared to previous compilations, over ±10 km in some specific areas (e.g. the Baltic Shield). Furthermore, the velocity structure of the crust is much more heterogeneous than in previous maps. EuCRUST-07 offers a starting point for numerical modeling of deeper structures by allowing correction for crustal effects beforehand and to resolve trade-off with mantle heterogeneities. **Citation:** Tesauro, M., M. K. Kaban, and S. A. P. L. Cloetingh (2008), EuCRUST-07: A new reference model for the European crust, *Geophys. Res. Lett.*, *35*, L05313, doi:10.1029/2007GL032244.

1. Introduction and Basic Model Assumptions

[2] The crust is the most heterogeneous layer in the Earth and its impact to the interpretation of deep structures can mask the effect of deep seated heterogeneities. It is, for instance, nearly impossible to separate the crustal and mantle effects in potential field and geothermal modeling without additional data on the crustal structure [e.g., *Kaban et al.*, 2004; *Artiemeva*, 2006; *Artiemeva et al.*, 2006]. It is still very difficult to minimize the trade-off between the crustal and upper mantle heterogeneities in seismic tomography, which remains the main tool to investigate the structure of the mantle. *Martin et al.* [2005] have reported that teleseismic tomography for SE Romania without applying sophisticated a priori 3-D crustal correction gives results, which are strongly contaminated in the uppermost 100–150 km depth by a significant effect from an incorrect crustal model. *Waldhauser et al.* [2002] have demonstrated that the non-linear inversion of the synthetic residuals without correcting for the 3-D crustal structure erroneously maps the crustal anomalies into the upper mantle. Therefore, reliable models of the upper mantle can be constructed only if the effect of the crust is reduced from the observed fields beforehand. Crustal models primarily based on existing reflection and refraction seismic profiles have been used for these purposes during the last decade. However, different models of the European crust are still inconsistent in many respects. In particular, differences of the existing Moho maps often reach and even exceed ±15 km (e.g. CRUST5.1 [*Mooney et al.*, 1998], CRUST2.0 [*Bassin et al.*, 2000] and SVEKALAPKO [*Kozlowskaya et al.*, 2004]). These discrepancies result from the coarser resolution of previous compilations (e.g. CRUST 2.0), which neglect small scale features, and differences of the employed data sets, in particularly based on non-seismic information. Consequently, the obtained results after corrections for crustal structure are different in many cases. For example, the residual mantle gravity anomalies obtained by different authors may differ up to about 100 mGal [e.g. *Yegorova and Starostenko*, 1999; *Kaban et al.*, 2004].

[3] The main purpose of this study is to construct a new high-resolution 3-D model (EuCRUST-07) of the European crust, which can be used as a starting point in a wide range of lithosphere and upper mantle studies. EuCRUST-07 is mainly based on existing seismic refraction, reflection and receiver functions studies, most of them carried out within the ILP program (Figure 1). Whenever possible we use detailed local compilations based on seismic data [e.g. *Kozlovskaya et al.*, 2004]. We refrain from using inferences from non-unique gravity field interpretations commonly employed in previous compilations. The study area is limited to 35°N–71°N, 25°W–35°E. EuCRUST-07 consists of three layers: sediments and 2 layers of the crystalline crust, the latter characterized by an average *P*-wave velocity determined from seismic data. Depth to the crystalline basement and Moho are the parameters most reliably determined in all kinds of seismic data. The situation with the inner crustal boundaries is more complicated. At least two layers within the crystalline crust are detected in most seismic sections; therefore, it has been decided to maintain this division in the generalized model. In the areas, where the crystalline crust consists of only one layer, having a constant velocity (e.g. in the Tyrrhenian Sea) or characterized by a gradual change (e.g. in the Western part of the Black Sea), we arbitrarily divide the crust in two layers of equal thickness having average velocities consistent with the seismic data. In the opposite case, several layers are joint to form one equivalent layer, e.g. in the East European Platform (EEP), where the velocity in the upper layer is calculated as a weighted average of upper and middle crust velocities. The final model (Data Set S1 of the auxiliary material)[1] is presented on a uniform $15' \times 15'$ grid.

[4] The employed local Moho maps are shown in Figure 1. When possible, we have verified these compilations and modified them in some details using available seismic profiles (Data Set S2 of the auxiliary material). All

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[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2007gl032244. Other auxiliary material files are in the HTML.

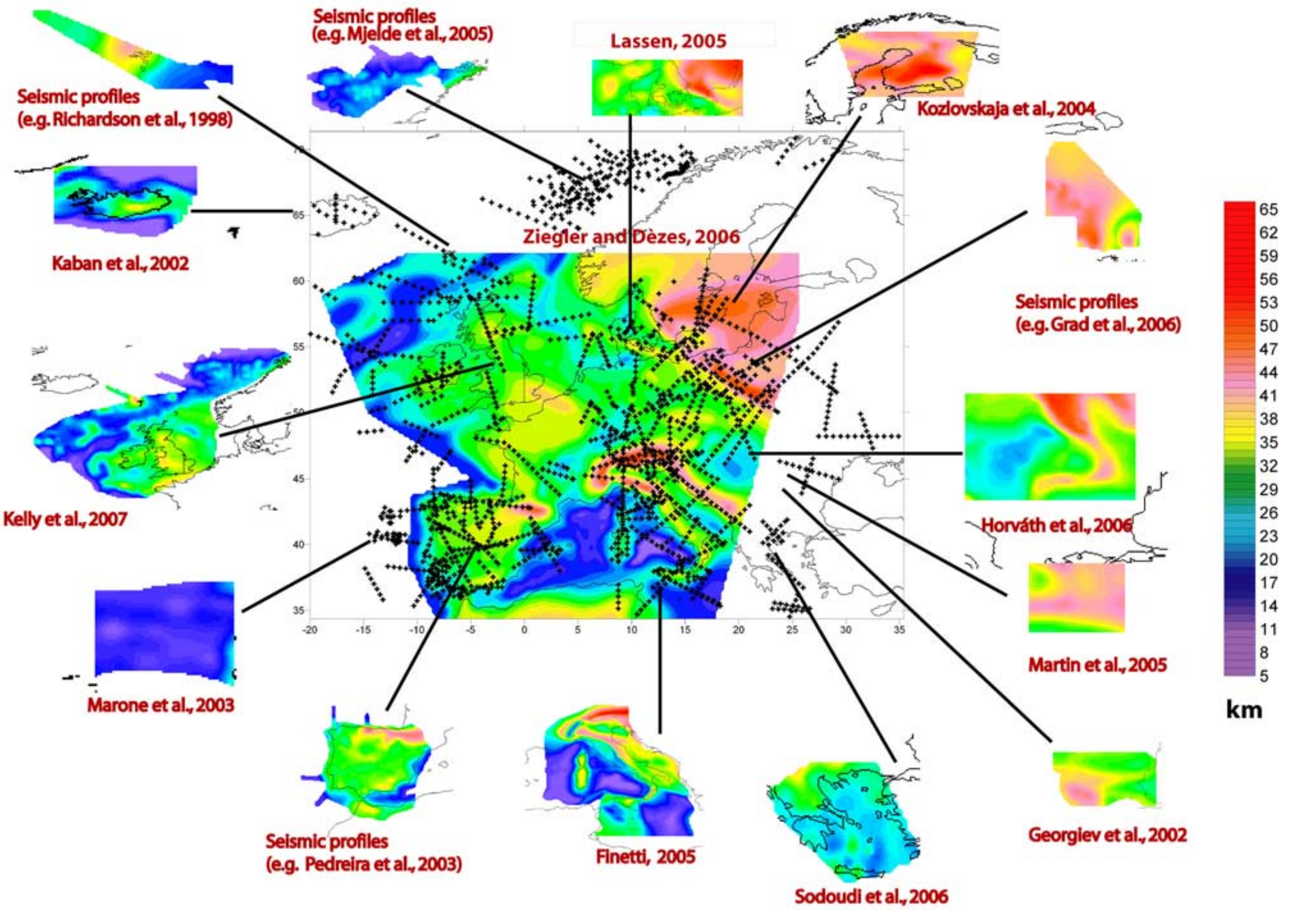

Figure 1. Moho depth (km) updated from *Ziegler and Dèzes* [2006] (34°N–62°N, 18°W–25°E) and extended (35°N–71°N, 25°W–35°E) including an array of new datasets. Dashed lines show the location of the seismic profiles incorporated.

the maps have been converted to the same resolution $15' \times 15'$. In the regions densely covered by recent seismic data, not included in the existing Moho compilations (e.g. in the Iberian Peninsula, where the results of the most recent seismic experiments are not incorporated in the *Ziegler and Dèzes* [2006] map, ZDmap) we interpolated the seismic profiles using a standard kriging method (SURFER, Golden Software package) to trace the Moho boundary. We merged all the compilations in a unified model giving a preference to the most robust. Typically we used detailed local studies, which are based on well specified sources. The regional ZDmap has been largely substituted by local compilations. For the part of the oceans not covered by seismic profiles, we assign Moho depths from the global model CRUST2.0 [*Bassin et al.*, 2000], for a part of Norway from the Geothermal Atlas of Europe [*Hurtig et al.*, 1992] and for a part of the EEP and the Black Sea from the compilation of *Kaban* [2001]. To produce a smooth transition between different maps we left some free space between the compilations. The size of the gaps corresponds to their resolution (from 30 km for the detailed maps to 100 km for the global CRUST2.0). The same kriging technique was used to interpolate the gaps. The velocity distributions within the crystalline crust layers are mostly based on the interpolated determinations (wide-angle seismic data), whereas for most of Fennoscandia we used the model of *Kozlovskaya et al.* [2004]. In several cases when the non-uniform data coverage does not allow for a robust interpolation, we increased the number of data by adding extra points in agreement with the position of local tectonic units with reliable determinations in other parts (e.g. in Norway). In the oceanic domain without seismic data we assigned *P*-wave velocities (V_p) of 5.5 and 6.75 km/s to the upper and lower crust, correspondingly. The final grid was also obtained using the kriging interpolation.

[5] The depth to basement is determined based on available maps and sedimentary thickness compilations (Figure S1 of the auxiliary material). These compilations were verified and in several areas modified (e.g. in the North German Basin and in the Adriatic Sea) using the seismic profiles collected. We do not specify a velocity structure of the sediments. Due to extremely strong heterogeneity (both lateral and vertical) of this layer it is difficult to integrate relatively sparse published data into a uniform model. On the other hand, the material properties of sediments (e.g. density) are much less related to velocity variations, while seismic tomography results are mostly biased by crystalline

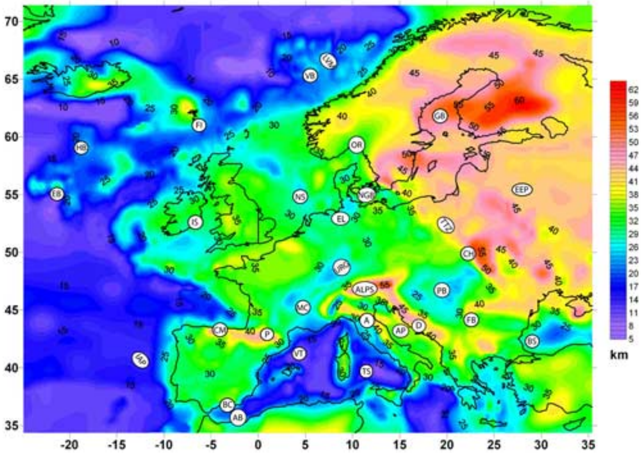

Figure 2. Moho depth (km). Abbreviations are as follows: A, Apennines; AB, Alboran Basin; AP, Adriatic Promontory; BC, Betic Cordillera; BS, Black Sea; CH, Carpathians; CM, Cantabrian Mountain; D, Dinarides; EB, Edoras Bank; EL, ElbeLineament; EEP, East European Platform; FB, Focsani Basin, FI, Faeroe Islands; GB, Gulf of Bothnia; HB, Hatton Bank; IAP, Iberian Abyssal Plain; IS, Iapetus Suture; LVM, Lofoten–Vesterålen margin; MC, Massif Central; NGB, North German Basin; NS, North Sea; OR, OsloRift; P, Pyrenees; PB, Pannonian Basin; TS, Tyrrhenian Sea; TTZ, Tesseyre–Tornquist zone; URG, Upper Rhine Graben; VB, Vøring Basin; VT, Valencia Trough.

crust heterogeneity. Therefore, we leave this problem for future regional and detailed studies.

[6] Below we highlight some principal features of EuCRUST-07 for the main tectonic units of Europe.

2. Crustal Model of Western and Central Europe

[7] The new Moho map and the average velocities in the upper and lower crust are shown in Figures 2, 3, and 4 respectively. In agreement with previous studies systematic differences in the crustal thickness and velocity between Western and Eastern Europe are found. However, we also observe a very strong heterogeneity of the crustal structure within these domains.

2.1. Fennoscandia

[8] The Moho depression beneath Central and Southern Finland and the Gulf of Bothnia is much more pronounced than in previous compilations (>60 km, 10 km deeper compared to CRUST2.0). This is the result of recent seismic experiments (SVEKALAPKO [*Kozolovskaya et al.*, 2004]). The boundary tends to rise to the west reaching a value of ~40 km in Sweden and of about 30–32 km beneath the Oslo rift and the Norwegian coast. Two local maxima of 40–43 km have been recently detected in southern Norway by a receiver functions study [*Svenningsen et al.*, 2007]. Westward to the Norwegian coast the Moho gradually shallows to ~20 km, while it deepens again to ~25 km at the transition to the oceanic crust in the Lofoten–Vesterålen margin and Vøring Basin, which is characterized by a thick, high velocity (>7.0 km/s) lower crust [e.g., *Mjelde et al.*, 2005]. The maximum velocity observed in this area (over 8.0 km/s) is interpreted as a deep crustal root of partially eclogitized rocks that formed during the Caledonian orogeny [*Raum et al.*, 2006]. Northward, in the Lofoten–Vesterålen margin, a decrease in the thickness of the lower crust is accompanied by a decreasing amount of breakup intrusives and extrusives. The crust in this area experienced only moderate extension, in contrast to the occurrence of major crustal extension in the southern Vøring margin [e.g. *Tsikalas et al.*, 2005].

2.2. EEP and Tesseyre-Tornquist Zone (TTZ)

[9] The Moho discontinuity is relatively uniform within the considered part of the EEP (40 to 50 km) and the crust is characterized by high P-wave velocities (~7.0 km/s) in the lower part except for some areas in the southwestern edge, where relatively low velocities (~6.75 km/s) are observed. By contrast, the upper crust is quite inhomogeneous, being characterized by alternation of low and high velocity zones [*Grad et al.*, 2006] with an average value of V_p of 6.3 km/s. The Moho depth beneath the TTZ in Central Poland is intermediate between that in the EEP to the east (~45 km) and the Palaeozoic Platform to the south-west (30–35 km). The upper crust is characterized by low velocities, reflecting

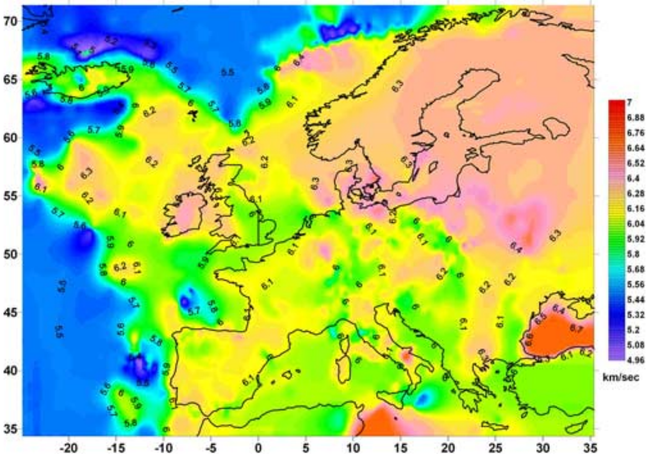

Figure 3. Average P-wave velocity in the upper crust (km/s).

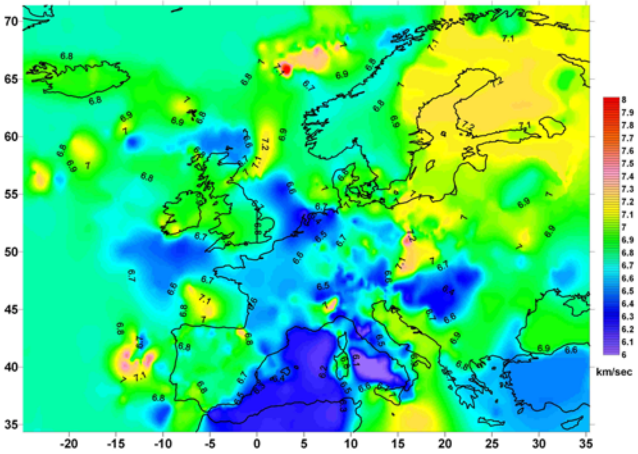

Figure 4. Average P-wave velocity in the lower crust (km/s).

a presence of metamorphic sediments or volcanic strata with $V_p < 6.0$ km/s, which depth reaches 18–20 km. On the other hand, velocities in the lower crust in this area are very similar to that of the EEP (~7.0 km/s) [*Guterch et al.*, 2006]. The crustal structure is more heterogeneous to the west from the TTZ. It is characterized by Variscan crust (e.g. in France) with thickness of about 30–35 km and slow V_p in the lower crust (~6.4–6.8 km/s), orogens with deep Moho (45–50 km) and extensional areas with very shallow Moho (e.g. ~10 km beneath the Tyrrhenian Sea) and low lower crust velocity (~6.0 km/s).

2.3. England and Atlantic Margin

[10] Beneath England and Ireland the Moho depth is between 30 and 35 km [*Kelly et al.*, 2007] and the velocity in the upper crust is between 6.0 and 6.4 km/s, while it increases in the lower crust from 6.7 to 7.0 km/s south of the Iapetus Suture Zone [*Landes et al.*, 2005]. The Moho shallows southwest of the Irish coast from 27 to less than 20 km over a horizontal distance of ~100 km, while the velocity decreases both in the upper and in the lower crust to 6.0 and 6.5 km/s, correspondingly. West of the Irish coast the continental crust thickness varies between 12 and 25 km [*Kelly et al.*, 2007], on account of the different amount of stretching to which it was subjected during the opening of the Atlantic Ocean [e.g. *O'Reilly et al.*, 1995]. The difference with CRUST2.0 is up to 15 km in this area. High velocities in the lower crust (~7.15 km/s) are observed beneath the Edoras and the Hatton Bank, presumably due to mantle underplating. The Moho deepens to 37–38 km beneath the Faeroe Islands and to 40–42 km approximately 100 km west of them, while the velocity in the lower crust is about 7.0 km/s. These high crustal thickness values (~10 km larger than in CRUST2.0) are a consequence of the Faeroe Islands location above the hottest core of the Icelandic mantle plume at the time of continental breakup [*Richardson et al.*, 1998].

2.4. North German Basin

[11] The Elbe Lineament, like the TTZ, represents another important geological boundary, where strong changes in the crustal thickness and composition are observed. The Moho beneath the North German Basin shallows from 35–34 km to 28–25 km from north to south of the Elbe Lineament, while V_p in the upper and lower crust decreases from 6.1 to 5.9 km/s and from 7.0 to 6.3 km/s, respectively. This strong change in the velocity of the lower crust possibly reflects a compositional transition from mafic to granitic rocks [e.g. *Scheck et al.*, 2002]. In the southeastern part of the North Sea similar changes in velocity and crustal thickness are present, suggesting that the WNW–ESE-striking Elbe Lineament continues into the Southern North Sea [e.g. *Scheck et al.*, 2002].

2.5. Carpathians-Pannonian Basin System

[12] The Carpathians, like the Alps, show strong changes in the crustal thickness, being characterized by a Moho depth of over 50 km in the Eastern part, which decreases to about 35 km in the Western part [*Horváth et al.*, 2006]. In the Southern Carpathians the Moho is between 37 and 42 km and reaches a maximum of ~44 km in the Focsani Basin [*Martin et al.*, 2005]. These recent determinations exceed values from the ZDmap for more than 10 km. The two layers of the crystalline crust areas are characterized by *P*-wave velocities of ~6.1 and 6.6–6.9 km/s respectively [e.g. *Środa et al.*, 2006]. The Pannonian Basin, which experienced strong extension, is characterized by a shallow Moho (~25 km) [*Horváth et al.*, 2006] and low upper (~6.0 km/s) and lower (~6.35 km/s) crust velocities.

2.6. Alps

[13] The Alpine region displays one of the main changes with previous compilations. Strong variations of the Moho depth, observed in recent seismic experiments [*Finetti*, 2005], are reflected in EuCRUST-07. Beneath the Western and Eastern Alps the European Moho plunges southward to ~40 and ~55 km, respectively. On the Adriatic side the Moho depth reaches 45 km beneath the Eastern Alps, while beneath the Western Alps a fragment of mantle-like material is observed, which is imbricated into the Alpine crust at the Insubric line [*Finetti*, 2005]. Therefore, the Moho depth is significantly reduced here (~20 km compared to the ZDmap) and the lower crust velocity is increased (~7.3 km/s). In the other parts of the Alpine chain the velocity of the upper crust shows normal values (6.0–6.1 km/s), while in the lower crust is anomalously low (6.4–6.6 km/s) [*Scarascia and Cassinis*, 1997].

2.7. Iberian Peninsula

[14] In the Iberian Peninsula the maximum depth of the Moho discontinuity is found beneath the Pyrenees and Cantabrian area (~45 km), significantly deeper than in previous maps (e.g. ZDmap), reflecting the subduction of the Iberian plate. In the same areas relative high velocities are found in the upper (6.25 km/s) and lower crust (from 6.7 to 7.20 km/s) [*Pedreira et al.*, 2003]. Strong changes in the Moho depth are also observed in the southeastern part of the Iberian Peninsula, where it shallows abruptly from 38 km beneath the Betics to 15 km beneath the Eastern part of the Alboran Basin [e.g. *Fullea et al.*, 2007]. In the same units a velocity decrease from 6.7 to 6.3 km/s in the lower crust is found. From the Western Iberian coast to the Iberian Abyssal Plain, the Moho shallows from 30 to 13 km over a horizontal distance of 300 km, showing a transition from continental to oceanic crust. In the Abyssal Plain the velocity in the basaltic lavas, representing the upper crust, decreases to 5.0 km/s, while in the highly serpentinized lower crust it increases up to ~7.5 km/s [*Chian et al.*, 1999].

3. Conclusions

[15] We have presented a new digital model of the crust for Western and Central Europe and surroundings that can be used as a constraint in modeling lithosphere and upper mantle structures. EuCRUST-07 demonstrates large differences with previous compilations, mostly resulting from including recently acquired seismic data. The discrepancies with the most recent regional Moho map of *Ziegler and Dèzes* [2006] reach –25 km (rms = 3.4 km), in the Ivrea zone, where the new map shows the updoming of a 10–20 km shallower Adriatic Moho, and +17 km in the Eastern Alps. Under the Cantabrian Mountains the new Moho is 8–10 km deeper, reflecting the subduction of the Iberian plate. Differences with the recent global map of *Kaban* [2001] reach −14-+17 km (rms = 3.9 km). Furthermore, when we average the local variations of EuCRUST-07 to bring it to the resolution of CRUST2.0, the difference remains signif-

icant from -19 km, in the Atlantic margin, to $+11$ km, in the Faeroe Islands and the Baltic Shield (rms = 4 km). The velocity structure of the crust turns out to be rather heterogeneous, even without considering regional variations from Western to Eastern Europe and the Baltic Shield, which are basically shown in previous models (e.g. CRUST2.0). Small scale features (e.g. ultramafic lower crust in the Vøring basin), revealed in EuCRUST-07 but not considered in the global models, also substantially influence the averaged values. The overall range of V_p variations in the upper part of the crystalline crust is 5.0–6.7 km/s and 6.0–8.4 km/s for the lower crust.

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