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# Metamorphic Core Complexes

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## Definition

Metamorphic core complexes result from horizontal lithospheric extension and form in low-viscosity lower crust when extension occurs at high rates and deformation within the upper crust becomes localized in detachment faults. They are oval shaped usually updomed structures in which mid-crustal basement rocks of higher metamorphic grade have been tectonically juxtaposed against low-grade upper crustal rocks.

## Introduction

Extension of Earth's lithosphere is one of the most fundamental processes that shape the face of our planet. Extension and breakup of continental lithosphere is key to understand the evolution of continents, the origin of sedimentary basins, and their hydrocarbon potential, as well as the thermohaline circulation in the oceans and thus global climate.

The most spectacular form of extension tectonics is the formation of metamorphic core complexes. Metamorphic core complexes mainly develop in continental crust, especially where it has been previously thickened by collisional processes. These processes heated up the thickened crust mainly by radioactive decay thereby weakening it and ultimately causing its failure. In oceans, metamorphic core complexes may form as well near mid-ocean ridges when magma supply is not efficient enough to accommodate extension (e.g., North Atlantic; Tucholke et al., 1998). This entry covers continental core complexes only.

## What Is a Core Complex?

Metamorphic core complexes are usually oval-shaped bodies in map view their long axis is typically some 20–50 km long. They result from localized extension, which drags out the middle or lower crust (metamorphic core) from beneath fracturing and extending upper crustal rocks and exposed beneath shallow-dipping extensional faults (detachments) of large areal extent (hundreds to more than one thousand square kilometers) (Lister and Davis, 1989) (Fig. 1). As the size of a fault is linked to its displacement, the large areal extent of the detachments indicates considerable tectonic transport along those faults. Displacement along core complex detachments is typically of the order of 20–80 km but may exceed 100 km (Foster and John, 1999; Ring et al., 2001; Brichau et al., 2006) and ultimately juxtaposes rock types with radically different geological histories (Fig. 2). The large displacements show that deformation during lithospheric extension is strongly localized during core complex formation.

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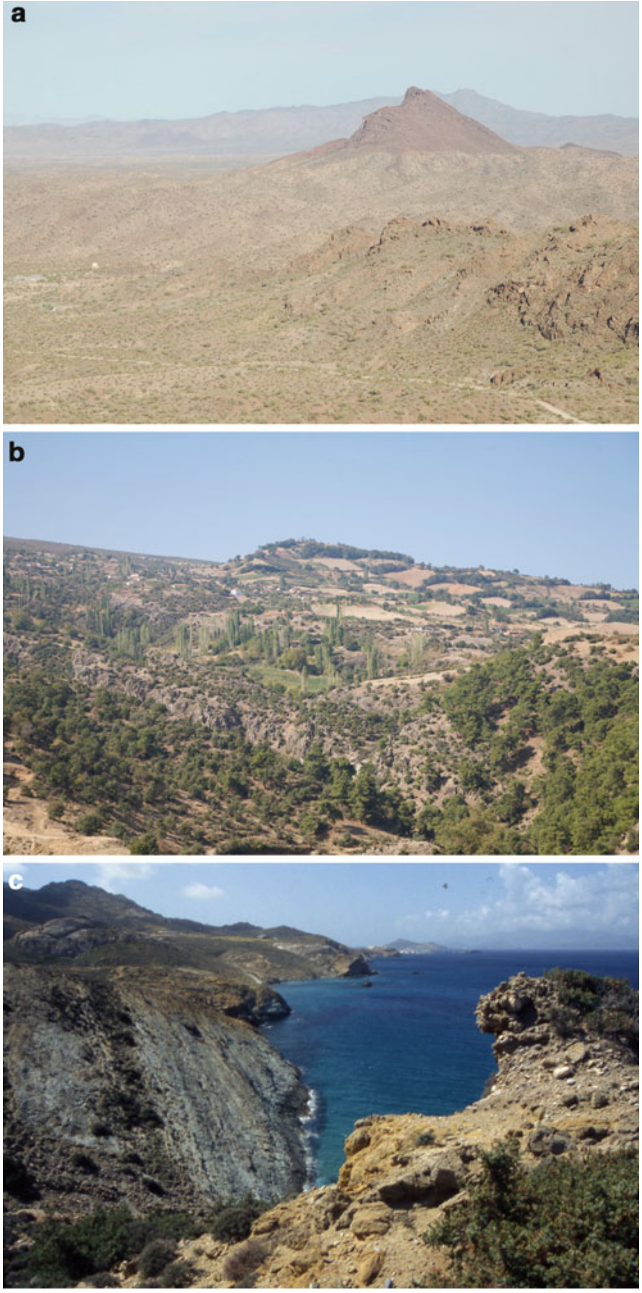

**Fig. 1** Field photos of detachment faults. (**a**) Rawhide Buckskin detachment in the Basin and Range province of the western USA. Yellowish-gray rocks in the lower two thirds of the photo form the metamorphic core; the red-brown hill is a tilted block of sediments in the hanging wall directly above the detachment fault, the latter of which is dipping very modestly to the left in this photo. (**b**) Kuzey detachment in the Menderes Massif of west Turkey. The surface in the upper left represents the detachment plane dipping at about 30° to the right; the hill above this plane in the middle of the photo represents hanging wall sediments. (**c**) Naxos detachment in the Aegean Sea. The view is onto the detachment plane, which is characterized by a marked stretching lineation representing the tectonic transport direction during extensional deformation. Sedimentary rocks in the foreground are coarse-clastic breccias that make up the basal section of the hanging wall (Olivier Vanderhaeghe provided photos in (**a**) and (**c**), Klaus Gessner for the photo in (**b**))

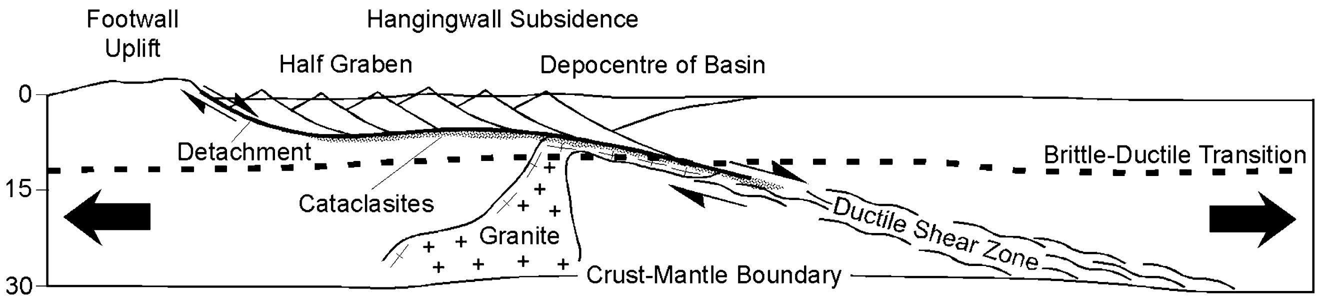

**Fig. 2** Idealized geometry of a continental core complex resulting from localized deformation as a response of horizontal lithospheric extension. Shallow-dipping ductile shear zone at depth grades into cataclastic shear zone and detachment fault in the upper crust. Note that in this model the crust-mantle boundary has been slightly exhumed as a result of extensional thinning of the crust. In cases where the lower crust has a lower viscosity, pronounced lower crustal flow may prevent thinning of the lower crust leaving the crust-mantle boundary flat

The detachments separating the metamorphic core from the upper crustal rocks are usually underlain by broader brittle-ductile to ductile extensional shear zones. The deformation in both is kinematically coordinated. In general, the detachments (and shear zones as well) dip at low angles (<30°). There has been some debate in the past whether these low-dip angles represent original values or whether the faults have been rotated from a steep orientation (≈60°) into their present low-angle position. Although it has been demonstrated that some low-angle detachments have been rotated from a higher-angle position (Axen et al., 1995; Gessner et al., 2001), there is incontrovertible evidence that many low-angle faults originated in a low-angle orientation (Wernicke, 1981; Lister and Davis, 1989; Cowan et al., 2003; Collettini and Holdsworth, 2004; Axen, 2007). A low-angle origin of the detachment faults readily explains the moderate variation in metamorphic grade along the crustal section exposed in the footwalls of core complexes (Lister and Davis, 1989).

The footwalls of core complexes are usually made up of middle/lower crustal metamorphic rocks that may be intruded by syn-extensional plutons (Fig. 2). The deeper parts of these plutons are frequently not or very weakly deformed; toward the detachments, they are overprinted by extension-related mylonites. In a number of cases, it has been convincingly shown that high-grade metamorphism and pluton emplacement are a consequence of core complex formation (Ring et al., 2010; Schulte et al., 2014), whereas in some other cases, temporal relationships between metamorphism, magmatism, and core complex formation remain elusive (Reynolds, 1982).

In general, rocks in the footwalls of core complex detachments show a distinct sequence of ductile deformation fabrics that were successively overprinted by brittle structures toward the structurally higher part of the shear zone underlying the detachment (Fig. 3). In the simplest case, high-temperature deformation structures may be preserved at the bottom of the shear zone. As the footwall is dragged up toward the surface, deformation becomes more localized, and lower-temperature deformation structures overprint earlier high-temperature structures in the upper portions of the evolving shear zone and are successively overprinted by cataclastic deformation once the footwall has reached the upper crust. The detachment faults at the top of the ductile shear

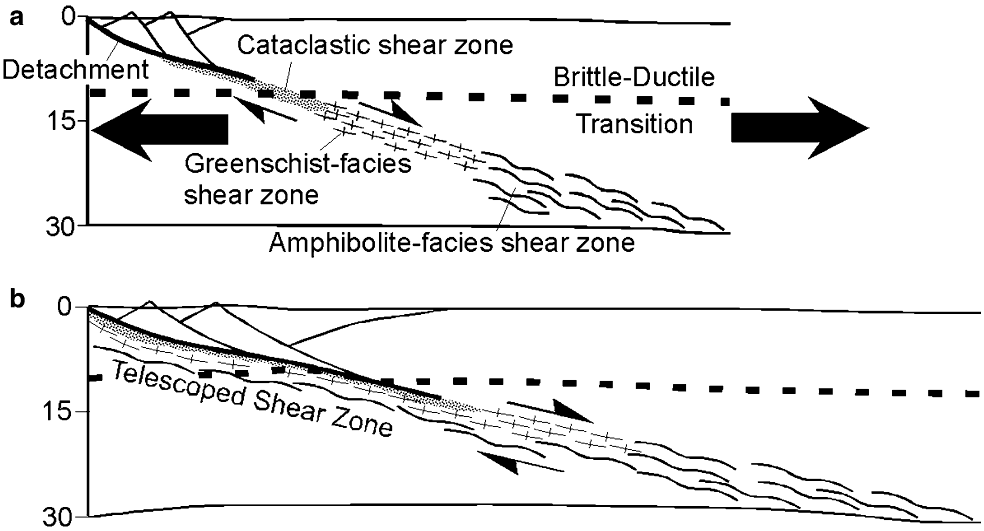

**Fig. 3** Idealized scheme for the evolution of ductile-to-brittle deformation in the uppermost footwall of core complexes. (**a**) Onset of core complex formation; extension is accommodated by detachment near surface, narrow cataclastic shear zone in deeper part of brittle crust, and greenschist- to amphibolite-facies shear zone in ductile lower crust below the brittle-ductile transition; note that shear zone is widening with depth (with increasing temperature). (**b**) As the amphibolite shear zone is dragged to the surface, it is overprinted by lower-temperature greenschist-facies deformation, which is in turn cataclastically overprinted as the shear zone moves into the upper crust

zone are basically upper crustal manifestations of the shallow-dipping, normal-slip shear zones (Reynolds, 1982; Davis, 1983). This simple, idealized overprinting sequence is usually not fully met because deformation is commonly heterogeneously distributed in nature.

The footwalls of metamorphic core complexes cool very rapidly at rates exceeding 50–100 °C $\mathrm{Myr}^{-1}$ as they are dragged up to the surface (Fitzgerald et al., 1993; Brichau et al., 2006; Thomson and Ring, 2006). Commonly thermochronologic ages that record true cooling through a certain closure temperature (e.g., fission-track and (U-Th)/He ages) are identical with error for minerals with different closure temperatures (Fitzgerald et al., 1993; Foster and John, 1999; Brichau et al., 2007). These cooling ages are also identical, or almost identical, to deformation ages from the extensional mylonites (Kumerics et al., 2005). Because most fault systems in metamorphic core complex are low angle, the amount of footwall exhumation is moderate (Deckert et al., 2002; Ring et al., 2003).

The upper crustal rocks above the detachments are often syn-extensional clastic sediments, which contain detritus of the metamorphic core. Therefore, the sediments provide evidence for syn-extensional exposure of the exhuming and uplifting footwall and record the exhumation history of the evolving core complex.

Core complexes also offer an opportunity to look into the problem of absolute versus relative displacement along tectonic faults. Shear-sense indicators in ductile and brittle shear zones provide evidence for the relative displacement of faults; they do not per se provide constraints as to the absolute motion of either hanging- or footwall relative to the Earth surface. However, in a core complex the metamorphic core usually has been juxtaposed against non-metamorphosed sediments in the hanging wall. This provides evidence for the absolute upward motion of the footwall relative to the Earth surface. The sediments of the hanging wall remained more or less stationary with respect to the Earth surface.

## Forms of Continental Extension and Thermal Stratification of Continental Crust

The metamorphic grade of high-grade rocks in the footwalls of exposed core complexes commonly shows that the rocks formed under a high thermal gradient exceeding 30 °C $\mathrm{km}^{-1}$. The high thermal gradient leads to a relatively hot and soft crust with a shallow brittle-ductile transition ($\leq$10 km depths) and a relatively high-strength contrast between the ductile lower crust and the brittle upper crust.

It has been shown that the thermal state of the continental lithosphere and its rheological structure control the variation between flow in the ductile middle and lower crust and localized deformation in the brittle upper crust and explains the location and architecture of core complexes (Buck, 1991). Continental rifts (like the East African Rift) form in relatively cold and strong lower crust. In hot, weak, low-viscosity lower crust, core complexes develop (Gessner et al., 2007). It is a general observation that there is a lack of a topographic low above-core complexes and that the crust-mantle boundary is flat in a number of core complexes (Gans, 1987). Both observations suggest that the lower crust is extremely weak and fluid (Buck, 1988). It is assumed that the hot and weak lower crust enables viscous flow to accommodate horizontal pressure gradients laterally across detachments, and this lower crustal flow may be sufficient to accommodate crustal thickness contrasts, thus leaving the crust-mantle boundary flat across the extended lithosphere as observed, for example, in the Basin and Range province (Block and Royden, 1990). In other words, as extension thins the crust, the fluid lower crust is being drawn in from the surrounding areas keeping topographic and crustal thickness gradients small. Because of these processes a hot crust is not thinning significantly during core complex formation, which makes it hard to break it apart to form a new plate boundary.

## Examples of Regions of Extended Lithosphere

The classical example of a region that has undergone large-scale continental extension is the Basin and Range province in western North America (Anderson, 1971; Armstrong, 1972, 1982). The Basin and Range records >100 % of extension that has in part been accommodated by the formation of numerous individual core complexes (Coney, 1980). Another well-studied example of large-scale continental extension is the Aegean Sea extensional province in the eastern Mediterranean (Jolivet and Brun 2010; Ring et al., 2010). In both settings, extension by core complex formation was followed by rift-type extension along high-angle normal faulting. The rift-type extension records a stage of much more limited horizontal extension at a later stage of continental extension.

Radiometric dating of extension-related structures shows that there is a pause in tectonic activity between the core complex and the rift stage. It appears that this lull records the time for the hot, formerly overthickened crust to cool down. Core complex formation acts as a mechanism (valve) of how the overheated crust can get rid of its excess energy (heat). The pronounced lower crustal ductile flow causes advective transport of low-viscosity material toward the Earth surface and thereby cools the crust, preconditioning it for rift faulting and eventual continental breakup. This lull in tectonic activity leads to a “messy” split of hot continents. Examples from the Liguro-Provençal basin (Italy/France) and the West Coast of New Zealand show that it took about 25–30 Myr from initial core complex formation to sea floor spreading (Rosenbaum and Lister, 2004; Schulte et al., 2014).

## Summary and Conclusions

Metamorphic core complexes are spectacular examples of large-scale continental extension, usually juxtaposing metamorphic lower crust against upper crustal rocks. They are bounded by low-angle normal faults that accommodate 10’s of kilometers of displacement. Metamorphic core complexes form when the strength contrast between ductile lower crust and brittle upper crust is high, which means when the thermal gradient is relatively high and therefore the brittle-ductile transition shallow ($\leq$10 km depths). These hot conditions of the ductile crust make it hard for the lithosphere to fully break apart to form a passive continental margin. Therefore, the lower crust needs to cool down before continental breakup can occur.

## Cross-References

- ▶ Backarc Basins and Backarc Spreading Center
- ▶ Intracontinental Rifting
- ▶ Oceanic Rift System
- ▶ Passive Plate Margin

# Bibliography

Anderson, R. E., 1971. Thin-skin distension in Tertiary rocks of southeastern Nevada. *Geological Society of America Bulletin*, **82**, 43–58.

Armstrong, R. L., 1972. Low-angle (denudation) faults, Hinterland of the Sevier Orogenic Belt, Eastern Nevada and Western Utah. *Geological Society of America Bulletin*, **83**, 1729–1754.

Armstrong, R. L., 1982. Cordilleran metamorphic core complexes—from Arizona to southern Canada. *Annual Reviews of Earth Sciences*, **10**, 129–154.

Axen, G. J., 2007. Research focus: significance of large-displacement, low-angle normal faults. *Geology*, **35**, 287–288.

Axen, G. J., Bartley, J. M., and Selverstone, J., 1995. Structural expression of a rolling hinge in the footwall of the Brenner Line normal fault, eastern Alps. *Tectonics*, **14**, 1380–1392.

Block, L., and Royden, L. H., 1990. Core complex geometries and regional scale flow in the lower crust. *Tectonics*, **9**, 557–567.

Brichau, S., Ring, U., Carter, A., Ketcham, R. A., Brunel, M., and Stockli, D., 2006. Constraining the long-term evolution of the slip rate for a major extensional fault system using thermochronology. *Earth and Planetary Science Letters*, **241**, 293–306.

Brichau, S., Ring, U., Carter, A., Monié, P., Bolhar, R., Stockli, D., and Brunel, M., 2007. Extensional faulting on Tinos Island, Aegean Sea, Greece: how many detachments? *Tectonics*, **26**(4), 19, doi: TC4009, 10.1029/2006TC001969.

Buck, W. R., 1988. Flexural rotation of normal faults. *Tectonics*, **7**, 959–973.

Buck, W. R., 1991. Modes of continental lithospheric extension. *Journal of Geophysical Research*, **96**, 20161–20178.

Collettini, C., and Holdsworth, R. E., 2004. Fault zone weakening and character of slip along low-angle normal faults: insights from the Zuccale fault, Elba, Italy. *Journal of the Geological Society*, **161**, 1039–1051.

Coney, P. J., 1980. Cordilleran metamorphic core complexes: An overview. In Crittenden, M. D., Jr., Coney, P. J., and Davis, G. H. (eds.), *Cordilleran metamorphic core complexes*. Boulder: Geological Society of America. Geological Society of America Memoir 153, pp. 7–31.

Cowan, D. S., Claddouhos, T. T., and Morgan, J., 2003. Structural geology and kinematic history of rocks formed along low-angle normal faults, Death Valley, California. *Geological Society of America Bulletin*, **115**, 1230–1248.

Crittenden, M. D., Coney, P. J., and Davis, G. H. (eds.), 1980. Tectonic significance of metamorphic core complexes of the North American Cordillera. *Memoir Geological Society of America*, **153**.

Davis, G. H., 1983. Shear-zone model for the origin of metamorphic core complexes. *Geology*, **11**, 342–347.

Deckert, H., Ring, U., and Mortimer, N., 2002. Tectonic significance of Cretaceous bivergent extensional shear zones in the Torlesse accretionary wedge, central Otago Schist, New Zealand. *New Zealand Journal Geology and Geophysics*, **45**, 537–547.

Fitzgerald, P. G., Reynolds, S. J., Stump, E., Foster, D. A., and Gleadow, A. J. W., 1993. Thermochronologic evidence for timing of denudation and rate of crustal extension of the south mountains metamorphic core complex and sierra estrella, Arizona. *International Journal of Radiation Applications and Instrumentation*, **21**, 555–563.

Foster, D. A., and John, B. E., 1999. Quantifying tectonic exhumation in an extensional orogen with thermochronology: examples from the southern Basin and Range Province. *Geological Society Special Publication*, **154**, 343–364, doi:10.1144/GSL.SP.1999.154.01.16.

Gans, P., 1987. An open-system two-layer crustal stretching model for the eastern Great Basin. *Tectonics*, **6**, 1–12.

Gessner, K., Ring, U., Johnson, C., Hetzel, R., Passchier, C. W., and Güngör, T., 2001. An active bivergent rolling-hinge detachment system: the Central Menderes metamorphic core complex in western Turkey. *Geology*, **29**, 611–614.

Gessner, K., Wijns, C., and Moresi, L., 2007. A dynamic process model for tectonic denudation of metamorphic core complexes. *Tectonics*, **26**.

John, B. E., and Foster, D. A., 1993. Structural and thermal constraints on the initiation angle of detachment faulting in the southern Basin and Range: the Chemehuevi Mountains study. *Geological Society of America Bulletin*, **105**, 1091–1108.

Jolivet, L., and Brun, J.-P., 2010. Cenozoic geodynamic evolution of the Aegean. *International Journal of Earth Sciences*, **99**, 109–38.

Krabbendam, M., 2001. When the Wilson cycle breaks down: how orogens can produce strong lithosphere and inhibit their future reworking. *Geological Society Special Publication*, **184**, 57–75.

Kumerics, C., Ring, U., Brichau, S., Glodny, J., and Monie, P., 2005. The extensional Ikaria shear zone and associated brittle detachments faults, Aegean Sea, Greece. *Journalof the Geological Society London*, **162**, 701–721.

Lister, G. S., and Davis, G. A., 1989. The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, U.S. *Journal of Structural Geology*, **11**, 65–94, doi:10.1016/0191-8141(89)90036-9.

Reynolds, S. J., 1982. *Geology and Geochronology of the South Mountains, Central Arizona*. Unpublished Ph.D dissertation, University of Arizona, Tucson, Arizona.

Ring, U., Layer, P. W., and Reischmann, T., 2001. Miocene high-pressure metamorphism in the Cyclades and Crete, Aegean Sea, Greece: evidence for large-magnitude displacement on the Cretan detachment. *Geology*, **29**, 395–398.

Ring, U., Thomson, S. N., and Bröcker, M., 2003. Fast extension but little exhumation: the Vari detachment in the Cyclades, Greece. *Geological Magazine*, **140**, 245–252.

Ring, U., Glodny, J., Thomson, S., and Will, T., 2010. The Hellenic subduction system: High-pressure metamorphism, exhumation, normal faulting and large-scale extension. *Annual Review of Earth and Planetary Sciences*, **38**, 45–76, doi:10.1146/annurev.earth. 050708.170910.

Rosenbaum, G., and Lister, G. S., 2004. Neogene and Quaternary rollback evolution of the Tyrrhenian Sea, the Apennines and the Sicilian Maghrebides. *Tectonics*, **23**, doi: 10.1029/2003TC001518

Schulte, D. O., Ring, U., Thomson, S., Glodny, J., and Carrad, H., 2014. Two-stage development of the Paparoa Metamorphic Core Complex, West Coast, South Island, New Zealand: hot continental extension precedes seafloor spreading by ~25 Myr. *Lithosphere*, **6**, 177–194, doi:10.1130/L348.1.

Thomson, S. N., and Ring, U., 2006. Thermochronologic evaluation of post-collision extension in the Anatolide Orogen, western Turkey. *Tectonics*, **25**, TC3005, 20 p, doi:10.1029/2005TC001833.

Tucholke, B. E., Lin, J., and Kleinrock, M. C., 1998. Megamullions and mullion structure defining oceanic metamorphic core complexes on the Mid-Atlantic Ridge. *Journal of Geophysical Research, B: Solid Earth*, **103**, 9857–9866.

Wernicke, B. P., 1981. Low-angle normal faults in the Basin and Range Province-Nappe tectonics in an extending orogen. *Nature*, **291**, 645–648.