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Review Article

Moho and magmatic underplating in continental lithosphere

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ABSTRACT

Underplating was originally proposed as the process of magma ponding at the base of the crust and was inferred from petrologic considerations. This process not only may add high density material to the deep crust, but also may contribute low density material to the upper parts of the crust by magma fractionation during cooling and solidification in the lower crust. Separation of the low density material from the high-density residue may be a main process of formation of continental crust with its characteristic low average density, also during the early evolution of the Earth. Despite the assumed importance of underplating processes and associated fractionation, the available geophysical images of underplated material remain relatively sparse and confined to specific tectonic environments. Direct ponding of magma at the Moho is only observed in very few locations, probably because magma usually interacts with the surrounding crustal rocks which leads to smearing of geophysical signals from the underplated material. In terms of processes, there is no direct discriminator between the traditional concept of underplated material and lower crustal magmatic intrusions in the form of batholiths and sill-like features, and in the current review we consider both these phenomena as underplating. In this broad sense, underplating is observed in a variety of tectonic settings, including island arcs, wide extensional continental areas, rift zones, continental margins and palaeo-suture zones in Precambrian crust. We review the structural styles of magma underplating as observed by seismic imaging and discuss these first order observations in relation to the Moho.

Contents

1. Introduction

The oldest crust was created from mantle derived magma by processes similar to underplating, which formed the original Moho. The formation of continental crust requires multiple melting sequences

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to form magma that, after solidification, will have the characteristic low average density of the crystalline basement (Arndt, 2013–this volume; Hawkesworth et al., 2013–this volume). The continental crust is subsequently affected by a variety of tectonic, erosional, depositional and metamorphic processes, which define the evolution of individual regions. Clearly, plate boundary processes, at both subduction and rift zones, play major roles in the shaping of the continental crust by tectonic and magmatic processes. These processes and their importance for forming the continental lithosphere have been widely discussed with focus on the various tectonic regimes. Additionally, the interaction of mantle upwelling (plumes) with continental lithosphere may play an important role in lithosphere growth, modification, and destruction both at plate margins and in intraplate regions. Mantle melting and infiltration of basaltic magmas are not restricted to the mantle part of the lithosphere, but often result in emplacement of magmatic bodies into the crust or at its base, i.e. as underplated material. In the following, we mainly focus on intraplate settings and the effects of the interaction of tectonic and magmatic processes that lead to intrusion of magma around the Moho.

Underplating and intrusion of magma into the crust and uppermost mantle are important processes for crustal formation and subsequent evolution because the addition of magma provides a non-tectonic way for the crust to grow and thicken. The resulting solidified magma bodies remain in the crust and uppermost mantle as images of past processes spanning the whole sequence of tectomagmatic processes, including crustal formation, orogenesis, rifting and break-up.

The initial Moho is a compositional boundary at the base of a primitive continental crust. However, during geologic evolution, other processes such as metamorphism may also affect the lower crust and uppermost mantle to form a Moho, which is not necessarily a boundary between different compositions, but instead a boundary between rocks in different metamorphic state with different seismic and density properties (Mengel and Kern, 1992). Because of the density contrast across the Moho, mafic magma rising from the mantle may experience neutral buoyancy around the Moho, in which case it may pond at this level to create a classic underplate of new crustal material at the pre-existing Moho. Given that the Archaean lithosphere is believed to have been formed by accretion of arc lithosphere and oceanic plateaus (Lee, 2006), underplating may have been a key process in the growth of continental crust in the Archaean because the underplated material may result in secondary melting of parts of the original crust (Fyfe, 1978, 1992). Underplating may also have been a major process in association with the formation of continental flood basalts (Cox, 1980), although its importance has not been confirmed by geophysical imaging so far. The thermal effects of crustal underplating and their consequences for seismic parameters have been discussed in depth by Furlong and Fountain (1986).

Early geophysical tests of the presence of underplated material below the continental Moho were based on acquisition of seismic and gravity data with relatively low resolution, and the results generally were in agreement with models of large, continuous layers of underplated material (e.g. Fowler et al., 1989). Recent seismic experiments at higher resolution have resulted in significantly improved images of the structure of underplated material and mafic intrusions in the continental crust, which has advanced the general understanding of the processes involved. In the following we introduce some of the early results, followed by a presentation and discussion of new findings mainly based on seismic models. They show that underplating is a complicated process which may take many expressions and may not just be related to ponding of mafic magma beneath the Moho. We therefore discuss structure and processes related to a wide variety of structural settings where magmatic processes have altered the depth interval around the Moho in the crust and uppermost mantle.

Identification of underplated intrusive mafic material on the basis of geophysical observations cannot be unique. The discriminators are high P- and S-wave velocity, high Vp/Vs ratio or Poisson' ratio and high density. However, these characteristics may also apply to granulites from the lower crust which have been metamorphosed into eclogite facies, and to some degree to serpentinized mantle peridotite which nevertheless tends to have lower density than the other rock types. Interpretations therefore have to incorporate other knowledge of the general tectonic setting. Reflection seismic images may further help the identification in cases when the magmatism creates sill like features, which are readily identified by this method, or in cases of large intrusive bodies that have cooled for long time to create a body with smoothly varying properties, which may be reflection free at seismic frequencies. Reflection seismic profiles often image changes from lower crustal reflectivity to a reflection free part of the lower crust, which potentially may indicate the presence of underplated material.

We include a wide range of processes into our definition of underplating, which is "addition of mafic magma to the lower crust and uppermost mantle around the Moho". The original concept of underplating consisted of a simplistic model where magma was ponding just below the Moho. Such underplated layers originally were conceived as having large lateral extent, but this has never been identified by geophysical imaging and may not exist. In the following we argue that underplating in our broad definition takes place in a wide range of tectonic settings (Fig. 1), and it plays a major role in the tectonomagmatic evolution of the lithosphere. A main conclusion is therefore that it is impossible to provide a simple definition of the term underplating.

2. Underplating and lower crustal reflectivity

There is some uncertainty about the origin of the ideas of underplating and when the concept was first proposed. Fyfe (1978) proposes that massive mixing processes occur near the base of the continental crust when mantle magma ponds near the Moho. He finds that such ponded material may be responsible for the formation of granitic magmas by mixing parts of the original magma with remolten crustal rocks, thereby leading to the distinct geochemistry of granites. Fyfe assumes that hotspots are the most likely source of the initial magma. He carries the arguments further (Fyfe, 1992) based on measurements of densities of various magma types from laboratory experiments. He finds that the densities of mantle derived magmas are higher than the average density of the continental crust and close to the density of the lower crust, at least at the advanced stages of magmatism, at the expected temperatures and pressures at the Moho. This provides a strong argument that magmas may accumulate (pond) at the Moho level.

Basaltic magmas may also penetrate into the crust. The style of interaction of high-density, mafic–ultramafic magmas with the crust and the geometry of intrusions which intrude into low-density crustal rocks is controlled by lithosphere rheology (Gerya and Burg, 2007). Elasto-plastic rheology that dominates at low temperatures favours upward magma propagation by crustal faulting and results in formation of sills and finger-shaped dykes in the crust. In case of high lithospheric temperatures, magmatic intrusions usually form large flattened mushroom-shaped plutons. Crustal heating caused by underplating and mafic intrusions causes crustal melting and granitic magmatism. It is generally believed that the time-scales for the latter are less than100,000 years irrespective of tectonic setting, and even when large volume of felsic magmas are produced (Petford et al., 2000). In the latter case, these magmas may solidify as granitic crust (e.g. Coldwell et al., 2011; Douce, 1999; He et al., 2011; Huppert and Sparks, 1988).

There are abundant geologic and petrologic arguments that substantial underplating must exist at the base of the crust (Peltonen et al., 2006; Zheng et al., 2012) but direct geophysical observations in cratonic areas generally indicate that underplated structures are relatively local (Gorman et al., 2002; Korsman et al., 1999; Thybo et al., 2003). However,