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Multiscale magmatic cyclicity, duration of pluton construction, and the paradoxical relationship between tectonism and plutonism in continental arcs

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ABSTRACT

The close relationship between crustal magmatism, an expression of heat dissipation, and tectonics, an expression of stress dissipation, leads to the question of their mutual relationships. Indeed, the low viscosity of magmas and the large viscosity contrast between magmas and surrounding rocks favor strain localization in magmas, and then possible “magmatic” initiation of structures at a wide range of scales. However, new data about 3-d pluton shape and duration of pluton construction perturb this simple geological image, and indicate some independence between magmatism and tectonics. In some cases we observe a direct genetic link and strong arguments for physical interactions between magmas and tectonics. In other cases, we observe an absence of these interactions and it is unclear how magma transfer and emplacement are related to lithospheric-plate dynamics. A simple explanation of this complexity follows directly from the pulsed, incremental assembly of plutons and its spatial and temporal characteristics. The size of each pluton is related to a magmatic pulsation at a particular time scale, and each of these coupled time/space scales is related to a specific process: in small plutons, we can observe the incremental process, the building block of plutons; in larger plutons, the incremental process is lost, and the pulsation, which consists of a cycle of injections at different timescales, must be related to the composition and thermal regime of the source region, itself driving magmatic processes (melting, segregation, and transfer) that interact with tectonic boundary conditions. The dynamics of pulsed magmatism observed in plutonic systems is then a proxy for deep lithospheric and magmatic processes. From our data and a review of published work, we find a positive corelation between volume and duration of pluton construction. The larger a pluton, the longer its construction time. Large/fast or small/slow plutons have not been identified to date. One consequence of this observation is that plutonic magmatic fluxes seem to be comparable from one geodynamic setting to another and also over various geologic time spans. A second consequence of this correlation is that small plutons, which are constructed in a geologically short length of time, commonly record little about tectonic conditions, and result only from the interference between magma dynamics and the local geologic setting.
The fast rate of magma transfer in the crust (on the order of cm/s) relative to tectonic rates (on the order of cm/yr) explain why the incremental process of pluton construction is independent of – but not insensitive to – the tectonic setting. However, in large plutonic bodies, which correspond to longer duration magmatic events, regional deformation has time to interact with the growing pluton and can be recorded within the pluton-wall rock structure. Magma transfer operates at a very short timescale (comparable to volcanic timescales), which can be sustained over variable periods, depending on the fertility of the magma source region and its ability to feed the system. The fast operation of magmatic processes relative to crustal tectonic processes ensures that the former control the system from below.

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1. Introduction

At the plate scale, magmatism (i.e. all processes associated with the formation, evolution, and transfer of magma) is directly controlled by lithospheric-plate dynamics, in the sense that plate divergence and convergence are responsible for the modification of the P, T, and X conditions leading to partial melting. This relationship is exemplified by the production of oceanic crust associated with basaltic tholeiitic magmatism at divergent plate boundaries and by the production and differentiation of continental crust linked to calc-alkaline and peraluminous magmatism at convergent plate boundaries. At the regional scale, numerous studies on plutons of various ages have shown that their location and internal structure are correlated with surrounding regional structures, and consequently seem to be controlled by tectonics (i.e. regional-scale deformation in response to lithospheric plate motion). Consequently, granitic plutons are commonly used in tectonic studies to reconstruct the geodynamic evolution of continental crust. The principal source of information is the structure of pluton–wallrock systems, whose evolution is controlled by the regional stress regime, the local geologic setting (geometry and thermal structure), and the dynamics of magma infilling. The structure of pluton–wallrock systems then allows us to study the interactions and the individual characteristics of both tectonic and magmatic processes during emplacement.

This close relationship between crustal magmatism, an expression of heat dissipation, and tectonics, an expression of stress dissipation, leads to the question of their mutual relationships. Indeed, the low viscosity of magmas, and consequently the sharp viscosity contrast between magmas and surrounding rocks, favor strain localization in magmas, and thus the possible “magmatic” initiation of structures at a wide range of scales (Tikoff and Saint Blanquat, 1997; Bons et al., 2008).

However, some new data and ideas challenge this simple geological image, and indicate some independence between magmatism and tectonics. For example, analysis of the 3-d shape of plutons from various tectonic settings has shown that the majority are tabular to funnel-shaped and that their shape evolves according to a power–law relationship, typical of systems exhibiting scale-invariant behaviour (McCaffrey and Petford, 1997; Cruden, 1998; Petford et al., 2000). A consequence is that the construction of plutons is controlled by a self organization process of magmatic origin, irrespective of the tectonic context. Another example is provided by recent data on duration and rate of pluton construction, which show that some plutons are constructed in less than 100,000 years (Saint Blanquat et al., 2001; Saint Blanquat et al., 2006; Michel et al., 2008), a duration which precludes any significant intervention and recording of syn-plutonic regional deformation during pluton construction. Thus, on the one hand we observe a direct genetic link, and some strong arguments for physical interactions between magmas and tectonics. Yet, on the other hand, we also observe an absence of these interactions, as it is not clear how magma transfer and emplacement are related to lithospheric-plate dynamics. In this paper, we describe how the recently recognized pulsed, or incremental, growth of plutons will help us resolve this apparent paradox.

The origins of ideas developed in our paper include: (1) pioneering work demonstrating that magma intrusion and tectonic rates do not operate at the same time scales (e.g., Paterson and Tobisch, 1992; Nyman et al., 1995); (2) the observation that some plutons may have an internal record which is only interpretable in terms of emplacement-related processes injection and magma chamber processes) and has nothing to do with external regional deformation during construction (Sylvester et al., 1978; Cruden et al., 1999; McNulty et al., 2000; Saint Blanquat et al., 2001; Harper et al., 2004; Barbey et al., 2008); and (3) work showing that pluton shapes seem to be controlled by internal processes which are independent of chemical composition and crustal tectonic regime (McCaffrey and Petford, 1997; Cruden, 1998; Petford et al., 2000; Cruden and McCaffrey, 2001).

In this paper, we first briefly summarize and then compare a series of petrostructural studies we have conducted on plutons of various sizes, constructed in various tectonic settings, but all related to the same geodynamic setting of arc magmatism. These intrusions include: (1) the Black Mesa pluton in the Henry Mountains, Utah, of Oligocene age and with no associated regional deformation; (2) the Mono Creek and Papoose Flat plutons, and Tuolumne intrusive suite in the Sierra Nevada and White-Inyos Mtns of California of late Cretaceous age and transpressional setting; and (3) the Tinos pluton in the Cycladic islands, Greece, of Miocene age and extensional setting. Based on these comparisons, we discuss the relations between the nature of the structural record and the tectonic setting of the studied plutons. We conclude that the incremental process of pluton construction is the same for all these plutons, with similar characteristics irrespective of their tectonic setting, age, and composition. We also show that the first parameter to check before interpreting the nature of the plutonic record is the total duration of pluton construction, which is itself directly related to the final pluton volume.

2. The plutonic structural record, a definition

The structural development of plutons is classically described as being recorded by the internal layering and fabrics. Layering can be defined as “the combination at any scale of layers differing by composition or texture” (Barbey, 2009). Fabric is formed by the shape preferred orientation (SPO) of minerals, and is defined by its orientation, shape, and intensity. Following Barbey (2009), three processes are involved in the formation and evolution of the structural record within a growing pluton: (1) injection processes (incremental growth, magma channelized flow, mingling, mixing, etc…); (2) magma chamber processes (hydrodynamic processes, crystal settling, etc…); and (3) tectonic processes (forces applied to the boundaries of the magmatic bodies inducing a deformation). In other words, any structural plutonic record can be interpreted as: (1) a record of deformation, either related to emplacement dynamics (injection) or to regional deformation, and/or (2) a magmatic record related to magma differentiation during cooling of magma pulses.

3. The construction of plutons, historical perspective

The classical view of pluton construction consists of a dichotomy between “forceful” or “active” type, including doming, diapirism and ballooning, versus “passive” or “permitted” type, including stoping, cauldron subsidence and associated sheeting. Permitted types were considered to characterize magma emplacement in the upper crust, in contrast with forceful types that were considered to work at greater depths (Pitcher, 1979). In addition, although the presence of a structural control on magma transfer and emplacement has long been recognized, this was primarily based on observed relationships between pre-existing structures and magma ascent, rather than on interaction between evolving tectonic structures and magma transfer. Hutton (1988) first questioned the interaction between magmatic and tectonic forces by hypothesizing that ‘active’ emplacement occurs when the magma infilling rate is greater than the rate of tectonic opening, and ‘passive’ emplacement when it is less, and examining all types of tectonic setting, including transcurrent, extensional, and contractional. Hutton proposed that the combination of these two processes could generate the variety of emplacement mechanisms observed in different plutons. A consequence is that most plutons could be considered syntectonic. This idea was addressed in a discussion on the so-called syntectonic paradigm by Karlstrom (1989), who stated that all granitoids are syntectonic in a broad sense, as they are emplaced into crust experiencing regional deformation, and that many and perhaps most of the granitoids are