Revision 1

Mafic Replenishments Into Floored Silicic Magma Chambers

Robert A. Wiebe

Department of Earth and Planetary Sciences, University of California at Davis
One Shields Avenue, Davis, California 95616, U.S.A.

Abstract

Commingling between contemporaneous mafic and felsic magmas is now widely recognized in a broad range of intrusions and intrusive complexes. These interactions are important features for two main of reasons: (1) the rapidly chilled margins of mafic magma against silicic magma commonly preserve the compositions of mafic liquids, and (2) because the mafic magma solidifies rapidly, the resulting (final) configurations of mafic and felsic magmas can provide insights into physical processes and changing viscosity contrasts and rheologies of magmas and felsic crystal mush during crystallization of the mafic magma.

Mingling of contrasted magmas was first recognized in the 1950s. Wider recognition of interactions between mafic and silicic liquids led to concepts of “net-veining” in the 1960s, “intramagmatic flows” (chilled basaltic layers separated by felsic cumulates) in the 1970s, and in the 1990s to “mafic-silicic layered intrusions” (MASLI), which could be as much as a few kilometers thick and more than 100 km^2 in area. It was quickly appreciated that these MASLI preserved stratigraphic records of mafic replenishments into silicic magma chambers floored by felsic crystal mush. Volcanic studies had anticipated the occurrence of this last type of intrusion on the grounds that extensive ponding of basaltic magmas beneath silicic chambers was seen to be essential to keep large silicic systems like Yellowstone active for millions of years. This paper looks at the history of changing perceptions and interpretations of magma mingling and whether or not “sill complexes” are distinct from mafic-silicic layered intrusions. The stratigraphy of mafic-silicic layered intrusions records changing magmatic compositions, events and processes in a temporal framework comparable to that provided by coeval volcanic rocks. As a result, careful study of MASLI has great potential for linking plutonic and volcanic processes and events.

Keywords: Magma mingling, granite, gabbro, net-veining, mafic-silicic layered intrusions

Introduction

Mafic and silicic plutonic associations have long fascinated field geologists and their students - probably because of the striking character of different geometric arrangements of the highly contrasted rock types and because of the implications for separate magmatic reservoirs at depth that brought the contrasted magmas together. Wilcox (1999) surveyed the history of ideas about mixing magmas from the 1850s to the 1970s in both volcanic and plutonic associations. Many early reports described rounded fine-grained mafic rock in association with granite, and some of these suggested that gabbro and granite were emplaced at nearly the same time (Lossen 1882; Erdmannsdorffer 1908 – in Wilcox, 1999). Composite dikes with basaltic margins and a silicic interior were widely described and particularly common in the British Tertiary, but all were interpreted as later injections of rhyolite after the basalt had solidified (e.g., Judd 1893). Although hybrid-looking rocks commonly occurred in other gabbro-granite associations, none were unambiguously interpreted as liquid-liquid interactions. Nonetheless, liquid-liquid interactions were considered a possible interpretation of hybridization (Harker 1904, Bailey and Thomas 1930). Reaction and metasomatism were other common explanations on into the 1960s (e.g., Compton 1955, Chapman 1962) for features that we would now recognize as mingling and hybridization between coexisting magmas. Surprisingly, it was not until the 1950s that a study unequivocally interpreted basalt-granite contacts to have formed initially between two liquids (Wager and Bailey 1953). Their observations led to several studies that similarly recognized liquid-liquid contacts (Bailey and McCallien 1956, Elwell et al. 1962, Blake et al. 1965) between gabbro and granite. Initially, nearly all studies suggested that silicic magma invaded gabbro, probably because the gabbro was the more abundant lithology and because silicic melt remaining after the basalt had solidified commonly intruded fractures in basalt. The name applied to many of these occurrences, “net-veining”, emphasized that interpretation (e.g., Windley 1965). We now know that “net-vein complexes” where silicic “veins” separate closely packed chilled, pillow-like bodies of gabbro, either in dikes or in larger plutons, formed by flow of basaltic magma into granitic magma (Snyder et al. 1997); these now might more properly be termed basaltic pillow mounds that formed within silicic magma instead of water (Wiebe et al. 2001). The term “net-veining” should probably be restricted only to occurrences where granitic veins intrude solid gabbro and liquid-liquid contacts are absent.

Since the 1960s, interactions between mafic and silicic magmas have been widely recognized around the world both in extensional and arc terranes of all ages (Table 1). These occurrences have provided many new insights into plutonic plumbing systems that potentially link with volcanic activity at the earth's surface. Some of the most volumetrically significant composite intrusions occur when mafic dikes rise through the crust and encounter silicic magma chambers in the upper crust: there basaltic flows on the floors of silicic chambers can build up to kilometers-thick accumulations (Wiebe 1993). It is here, particularly, where composite intrusions match inferences from volcanic studies: that under-plating of basaltic magmas is essential in explaining the longevity of large silicic systems – e.g., Long Valley (Hildreth and Wilson 2007, Wark et al. 2007) and Yellowstone (Hildreth et al. 1991).

The purpose of this paper is to trace the history of the changing interpretations of mafic-silicic magma interactions and composite intrusions since the 1950s, leading to the recognition that basaltic magmas commonly pond within silicic chambers. It includes a review of work that led to the concept of a mafic-silicic layered intrusion (MASLI) and the currently known range of occurrences throughout the geologic record of basaltic injections into floored chambers of more silicic magmas. It does not focus on the history of ideas on mixing or hybridization, since Wilcox (1999) has ably reviewed that subject. A brief review of changing perceptions of granite origin and volcanology is essential to provide a broader context. This paper also addresses some current controversies in the interpretation of characteristic features of MASLI, and closes with a look at what MASLI have contributed to our understanding of emplacement and solidification of composite plutonic bodies and their connections to volcanic activity.

Evolving concepts of granite formation, magma chambers and volcanism

In the last fifty years or so, there have been many new insights into the emplacement and crystallization of granitic plutons. Although granitization, metasomatism and replacement were still considered significant emplacement modes in the late 1950s (e.g., Compton 1955; Buddington 1959), experimental studies of the granite system (e.g., Tuttle and Bowen 1958) led to overwhelming support for emplacement and crystallization of silicic magma. Magma, of course, consists of melt and crystals (+/- vapor), and from the 1950s to the 1980s, the proportion of crystals in the magma during ascent and emplacement was commonly considered substantial (e.g., “addition of crystal-charged magma”, Davis 1963, p. 331). For some, the crystal cargo was assumed to be “restite” – unmelted crystals from the partially melted source rocks (Chappell et al. 1987; Chappell 1997). For plutons at mid-crustal levels, diapirs or nested diapirs were widely proposed (Buddington 1959; Paterson and Fowler 1993), as was “ballooning” – feeding an expanding and crystallizing chamber by dikes of silicic magma (Akaad 1956). Experimental studies of natural granitic rocks indicated that granodiorite and tonalite samples when brought to the expected conditions of crystallization (e.g., 900°C and 2 Kb water pressure) still retained abundant unmelted crystals (Piwinksii and Wyllie 1968). To explain this, they suggested that the magma was emplaced with a high percent of crystals because they apparently assumed the samples they studied represented the magmas that fed the intrusion.

Problems encountered with both diapirs and balloons (Paterson and Vernon 1995, Hutton and Siegesmund 2001) and improved knowledge of silicic melt properties (temperature, viscosity, volatile content) led many workers in the 1990s to propose growth of plutons through multiple episodes of ascent of crystal-poor magma in dikes (Clemens and Mawer 1992; Petford et al. 2000). With the expectation that silicic intrusions were fed by crystal-poor silicic liquids, not crystal-rich mush, it became possible to envision, at least in some cases, active magma chambers that could undergo fractional crystallization and replenishment, and feed volcanic eruptions. The probable existence of crystal-poor magma chambers, at least at times, increased the likelihood of crystal accumulation on a chamber floor, and many recent studies provide strong support for that process (Collins et al. 2006; Walker et al. 2007). So the experimental results of Piwinskii and Wyllie (1968) can be explained in a different way: relative to the magmas emplaced into the intrusion, the samples probably lost as much as 30% liquid – they were, in a sense, cumulates (Irvine 1982).

In the 1970s, volcanologists were increasingly aware that magma chambers beneath silicic volcanic systems commonly contained a range of magma compositions - particularly from compositionally variable ash-flow sheets, which were recognized to provide an inverted record of a chamber with the least evolved deeper magmas residing at the top of the ash-flow (Lipman et al. 1966; Christiansen 1979). Many volcanic centers were also known to produce erupted material with a wide compositional range – e.g., Askja (Sigurdsson and Sparks 1981) and Crater Lake (Bacon and Druitt 1988), and some workers proposed that compositionally diverse magmas fed these chambers (Eichelberger 1978, Eichelberger et al. 2000). In some systems the likely role of crystal fractionation in magma chambers was increasingly supported by the evolution of erupted compositions (Bacon and Druitt 1988). Volcanologists also began to see indirect evidence for emplacement of basaltic magmas within silicic chambers: (1) contemporaneous basaltic vents on the flanks of silicic volcanic centers (Hildreth et al. 1991), (2) thermal considerations suggesting heat from basalt was needed to explain the life-span of these centers and (3) the occurrence of mafic enclaves within erupted rhyolites (Eichelberger and Gooley 1977). Increased interest in the physics of magma chambers led to a growing appreciation of physical processes likely to act in magma chambers that fed eruptions (Sparks and Huppert 1984, Huppert and Sparks 1984, Turner 1984, and Clark et al, 1987).

By the late 1970s, substantial volumes of basaltic magma were presumed to have accumulated under large rhyolite calderas like Long Valley and Yellowstone (Christiansen 1979). One disconnect between the volcanic record and the plutonic record, was the apparent scarcity of large composite intrusions comparable to those inferred to exist. Although the only two, layered composite bodies recognized by the mid-1970s (Blake 1966, and Wiebe 1974a, b) were too small to appear to be relevant, the criteria for recognizing such bodies became available and would, within the next 20 years, lead to the discovery of larger composite layered bodies of more appropriate size.

From net-veining to intramagmatic basaltic flows

The idea that two contrasted magmas might encounter each as liquids had long been considered a possible explanation for some composite dikes and hybrid rocks (e.g., Judd

1893, Harker 1904). Nonetheless, before 1953 finer-grained margins of mafic rocks were typically attributed to metamorphism or reaction with granitic magma (Richey 1937, Bishop 1964), fusion by gas streaming brought in by vein material (tuff) (Reynolds 1951) or metasomatism (granitization) (e.g., Chapman 1962). Then in 1953 Wager, working in St. Kilda, Scotland, and Bailey, working in Slieve Gullion, Ireland, independently came to the same conclusion: that the fine-grained margins of basaltic rocks against granite were due to chilling because of the temperature contrasts of two contemporaneous magmas, and, together in their 1953 paper, they established criteria for recognizing a basaltic chill against a granitic melt, and pointed out that the much higher solidus temperature basalt explained why, on cooling, it was so common to see later injections of silicic magma (back-veining) into basalt and gabbro (Wager and Bailey 1953). Bailey and McCallien (1956) revisited Slieve Gullion, focusing on the sequence of ~ horizontal interlayered basaltic (dolerite) and felsic layers with dolerite having basal chills on underlying felsic layers. Some of the dolerite layers consisted of chilled pillow-like bodies separated by silicic veins. Where Reynolds (1951) had interpreted these relations as metamorphosed pillow lavas, Bailey and McCallien (1956) believed they “resulted from entry of basic magma into relatively cool acid magma” (p. 484). Volcanic studies provided further support for commingling of basaltic and granitic magmas in plutonic rocks. Bailey and McCallien (1956) cited a study of commingling and mixing basalt and rhyolite in Yellowstone (Wilcox 1944). At a later date Gibson and Walker (1964) recognized composite dikes (basalt margins and rhyolite interior) that fed composite rhyolite-basalt lava flows in eastern Iceland, showing a clear link between plutonic and volcanic phenomena.

These papers triggered a renewed interest in mafic-silicic complexes, and many papers on new field studies were published into the mid 1960s. Slieve Gullion, Ireland, drew particular attention: it had been studied closely from the 1930s (Richey and Thomas 1932, Reynolds 1941) and had recently been restudied by Reynolds (1951), who re-interpreted the Tertiary complex as "highly metamorphosed basaltic and rhyolite lava-flows, agglomerates and tuffs, together with some gabbro sills" (Reynolds 1951, p. 85). She strongly disagreed with Wager's interpretations of the rocks (Reynolds 1953, 1961) and provided a stimulus for subsequent workers to document their observations carefully. Elwell (1958) studied the many silicic pipes that occur in a basally chilled dolerite layer and recognized that the dolerite must have been partially molten when the pipes were emplaced and that the source of pipes was the granitic layer beneath the dolerite. Bailey and McCallien (1956) carefully documented the evidence for co-existing basaltic and granitic magmas and effectively refuted Reynolds' (1951, 1953) metamorphic interpretation.

In the next several years, "net-vein complexes" (Fig. 1) were studied in the Channel Islands (Elwell et al. 1960, 1962), Greenland (Windley 1965), Ardnamurchan, Scotland (Skelhorn and Elwell 1966) and Iceland (Blake 1966). Elwell and his colleagues as well as Windley (1965) presented the then-dominant view of their formation: that silicic veins invaded a larger, homogeneous and partially molten mass of gabbro that was capable of fracturing. The description in Elwell et al. (1962) recognized that the veins did not have matching walls and that the resulting bodies of chilled gabbro resembled rounded pillows or tubes (Elwell et al. 1962, Figure 5, p. 222). The relationships described in these papers were subsequently reviewed in two widely read papers: Blake et al. (1965) and Walker and Skelhorn (1966).

Windley (1965) described and illustrated with numerous field photos a wide range of relations in mafic-silicic associations in Proterozoic rocks in Greenland, and particularly concentrated on net-veining. For these associations he rejected the simultaneous injection of basaltic and granitic magmas and proposed these three steps to their origin: (1) rheomorphism at depth of granitic rocks, (2) granitic material introduced along the walls of the gabbro and penetrated inward in contraction cracks in the gabbro and (3) granitic veins formed by reaction of granite with diorite and granite replacement to produce the rounded shapes (Windley 1965, p. 57).

There were several problems, some recognized then and others not, with forming a net-vein complex by injecting felsic veins into a homogeneous mass of partially molten gabbro. Beyond some doubt that gabbro in that state would fracture in such a way to provide entry of felsic magma as thin veins, Elwell et al. (1962) recognized that there was no correlation between the thickness of the felsic vein and the degree of chilling of the basalt, and felt uneasy with that. They also wondered how so little felsic material could chill the margins of the gabbroic bodies. They suggested that abundant gas streaming (fluidization) must have occurred prior to vein injection. They were apparently not concerned why felsic veins intruding the gabbro did not become superheated, being surrounded by so much hot gabbro, and mix into the partially melted gabbro. Further, they recognized that the veins were quartz diorite to granodiorite with up to 75% euhedral plagioclase, 2-3 mm in diameter, and 10-25% mafic minerals (mainly hornblende) with minor, commonly, granophyric matrix. These textures and compositions now would be more likely interpreted as those of a cumulate than an injected liquid (Collins et al. 2006; Walker et al. 2007).

Although Bailey and McCallien (1956) suggested it for Slieve Gullion, Blake (1966) at Austurhorn, Iceland, explicitly recognized and carefully provided observations that demonstrated a mafic-silicic "net-veined" complex was produced by tholeiitic basaltic magmas flowing sequentially into a rhyolitic chamber - not by silicic magma invading gabbro, thereby resolving many of the problems just mentioned (Fig. 2). "The basic pillows represent originally liquid inclusions of basic magma which were emplaced in liquid acid magma in a manner analogous to the extrusion of pillow lavas emplaced into water. The basic magma chilled against acid magma, and formed a solid or semisolid "skin" around the pillows. This skin inhibited mixing of the two magmas at pillow contacts. The basic pillows remained in a plastic condition for a short time after their intrusion, and during this period they were able to change their shapes . . . and hence were able to accommodate themselves to the shapes of adjacent pillows" (Blake 1966, p. 904). "The thin acid layers between closely spaced pillows may best be explained by the gravitational settling of the pillows on top of one another and the consequent squeezing out of most of the acid magma from between the pillows. This would explain why the degree of chilling of the pillow margins has little relation to the volume of silicic magma between the pillow" (p. 905). In these statements Blake implied that the pillows and sheets accumulated on the floor of a silicic magma chamber. After Blake's 1966 publication, and into the 1970s, most studies of mafic-felsic interactions were focused on mingling or mixing of magmas in composite dikes (e.g., Gunn and Watkins 1969, Wiebe 1973, Vogel and Wilband 1978) or small composite intrusions (Vogel and Walker 1975).

A small, layered gabbro-diorite intrusion near Ingonish, Cape Breton Island, Nova Scotia provided new lines of evidence for basaltic injections into a floored chamber of more silicic magma (Wiebe 1974a, b). This intrusion was emplaced in a continental arc setting and involved injections of hydrous high-Al basaltic magmas into an intermediate (andesitic?) magma chamber that initially produced hornblende + plagioclase cumulates that varied upward from diorite to quartz diorite and recorded incoming of cumulus biotite, titanite and quartz at increasingly higher levels. Average plagioclase compositions varied upward from about An_{50} to An_{30} (Wiebe 1974b). The basaltic input formed basally chilled layers from 0.5 to 12 meters thick. Layers less than a few meters thick typically had chilled tops and bottoms and were commonly separated by only a few cm of diorite (Fig. 3a). Where basaltic layers rested on thicker layers of diorite they typically had strongly chilled, highly irregular, lobate bases (Fig. 3b). Two main lines of evidence indicated that the basaltic layers were deposited on a chamber floor and beneath a crystal-poor magma. First, when an upper layer extended further than an underlying one, the upper layer flowed over the lower nose and continued flowing at the same level as the lower layer, providing evidence that both were deposited on a subhorizontal magma chamber floor. Second, layers greater than 6 meters thick typically had tops that lacked a chilled margin and graded up into diorite containing mafic enclaves. Upward, the enclaves decreased in size and increased in the degree of hybridization (Fig. 3c). These relations recorded disruption of the upper chilled margin, upward convection of partly crystallized basalt in dioritic liquid above the basalt layer, and deposition of diorite crystal mush and mafic enclaves as convection waned. For these reasons Wiebe (1974a) described the mafic layers as "intramagmatic flows" analogous to lavas at the earth's surface.

Basaltic dikes of similar composition cut the layered gabbro-diorite and may have fed basaltic layers at higher stratigraphic levels. Steep cylindrical pipes (1-2 meters in diameter) of remobilized diorite and mafic enclaves also cut the diorite. One fortuitous set of exposures showed a clear connection between the top of a pipe and a layer of mafic enclaves within the diorite, thereby again demonstrating the presence of a magma chamber floor that would been otherwise invisible (Wiebe 1974a, Figs. 15, 16).

Increased recognition of mafic-felsic complexes

Throughout the remainder of the 1970s and into the early 1990s, many papers reported on mafic-felsic complexes, for the most part concentrating on mingling and mixing processes to produce hybrids (e.g., Gamble 1979, Vogel et al. 1984, Brown and Becker 1986, Mattson et al. 1986). The origin of mafic enclaves within granitic plutons also received much attention. A landmark paper by Vernon (1984) established criteria for recognizing enclaves in granite that formed by quenched mafic to hybrid magma.

During this time period several workers recognized chilled mafic layers or layers of abundant mafic enclaves within felsic plutonic rocks. These were either interpreted as having been deposited on a silicic chamber floor or emplaced into homogeneous, incompletely crystallized felsic crystal-rich material. In the Massif Central of France, Barbarin (1988) recognized that the Piolard diorite (a tabular body about 1 km in diameter and a few hundred meters thick) sat with a basally chilled margin on top of the

Saint-Julien-la-Vetre monzogranite and was overlain by the same monzogranite with abundant dioritic inclusions (Barbarin 1988, Figs. 2, 7). The upper contact of the diorite was irregular with evidence for mechanical mingling and mixing, which he attributed to convection in overlying monzogranite magma due to heat from the top of the diorite layer.

Associated with the Nain anorthosite complex, the Proterozoic Newark Island layered intrusion contains an exceptional suite of cumulates ranging from troctolites and gabbros to quartz monzonites and intermediate hybrid rocks (Wiebe 1988). It was divided into a lower mafic Layered Series, about 3 km thick, and a much larger Hybrid Series consisting of a sequence of basally chilled troctolitic to gabbroic layers, typically hundreds of meters thick, that graded upward through 10s of meters at the top to hybrid rocks with varying proportions of resorbed, coarse-grained feldspars (sodic plagioclase and alkali feldspar) and a fine-grained mafic matrix and, in some layers, to coarse-grained two-pyroxene granite. The hybrid rocks were thought to form at the upper contact of troctolitic layers with overlying silicic magma. Kolker and Lindsley (1989) described a similar mafic-felsic layered body, the Maloin Ranch pluton, associated with the Proterozoic Laramie anorthosite complex. It contained chilled layers of fine-grained monzonite and biotite gabbro within coarse-grained leucocratic monzosyenite to quartz syenite. The compositions of these chilled layers closely matched the compositions of dikes elsewhere within the Laramie complex.

A tabular and layered body of gabbro to monzodiorite occurs in the Cordillera del Paine granitic pluton of southern Chile (Michael 1991). While the base of the mafic body was not exposed, individual mafic layers were chilled against underlying thin, irregular layers of more felsic rock in the lower gabbros. In the upper part of the mafic body, more evolved mafic rocks (monzodiorites and quartz monzodiorites) were also chilled against thin irregular more felsic layers and in contact with the overlying granite. Michael (1991) concluded that the mafic rocks were emplaced into and flowed across a granitic magma chamber floor. A superb set of recent papers (Leuthold et al. 2012, 2013 and 2014) sheds much new light on the origin of this complex (see below).

In a paper mainly focused on mafic enclaves in granitoids, Blundy and Sparks (1992) also described a series of tonalitic to dioritic rocks interlayered with chilled and fragmented mafic rocks (the Val Freda complex) that appears to have much in common with these other intrusions. They thought that the mafic sheets were emplaced into (apparently homogeneous) “hot tonalite probably still containing some melt” (Blundy and Sparks 1992, p. 1049), rather than at a rheological transition within a magma chamber. I visited the Val Freda complex briefly with Blundy and others in 2006. The relations we observed between tonalite and chilled gabbroic layers and lenses appeared similar to those in the Ingonish intrusion, though in most instances, it was impossible to tell if the gabbros were randomly emplaced or represented a stratigraphic sequence. In only one outcrop was it possible to see that an upper layer was younger than the one below: in this case, the upper layer disrupted and removed the upper chilled margin of the underlying layer (Fig. 4).

In the early 1990s, Chapman and Rhodes (1992) and Wiebe (1993, 1994) described three Paleozoic composite layered intrusions along the coast of Maine. The Isle au Haut igneous complex (Chapman and Rhodes 1992) consists of alternating thick basally chilled gabbro layers (from 7 to 106 meters thick) and coarser-grained dioritic layers (from 7 to 24 meters thick), which become increasingly evolved upward to quartz monzodiorite at the top, above which occurs a thick granite layer beneath a roof of coeval rhyolite. Chilled mafic pillows are common just beneath the gabbroic layers, and the underlying dioritic layers have fed prominent cylindrical felsic pipes that typically widen upward, acquiring gradational contacts with the gabbro in contrast to chilled gabbroic margins near the base. The Cadillac Mountain intrusive complex (Wiebe 1994) has a section roughly 2 km thick of interlayered gabbroic, dioritic and granitic rocks that was emplaced into the lower portion of the Cadillac Mountain hypersolvus granite. The relatively minor felsic layers in the gabbro-diorite unit range from felsic diorite to granite. Many layers grade upward in only a few meters from diorite to granite and record steep compositional variation in magmas at the base of the chamber between the rapidly solidifying basalt and overlying silicic magma. This body is also associated with coeval rhyolite and basalt (Seaman et al. 1999).

Mafic-silicic layered intrusions

The third composite body in Maine, the Pleasant Bay layered intrusion (Wiebe 1993), consists of more than 90% gabbro and mafic diorite and lacks an overlying body of granite. So it was no surprise that it was initially mapped as a layered gabbro intrusion (Bickford 1963). I was fortunate to meet and talk with Bickford at a 1988 GAC/MAC meeting in St John’s, Newfoundland, where he said that he did remember seeing some features associated with the scarce felsic layers in the Pleasant Bay intrusion that greatly resembled those involving mingling and mixing between basalt and granite, which, in an earlier talk, I had described in the Newark Island layered intrusion (Wiebe 1988). In our conversation, he mentioned that he and Chapman presumed the felsic layers were later and therefore not important for the study of the layered gabbros. So he encouraged me to begin a restudy of the body. (Bickford's thesis advisor, C. A. Chapman, had recently interpreted pillow-like bodies of basalt in a granite dike as products of granitization of a homogeneous basalt dike, leaving only rounded remnants of basalt in granite (Chapman 1962). So Chapman was apparently not receptive to the concept of magma mingling and likely rejected it as a reasonable interpretation of the field relations.) The intrusion turned out to provide superb exposures that recorded many types of interactions between basaltic injections with resident silicic crystal mush and liquids – all in the context of a layered intrusion.

I eventually described the Pleasant Bay pluton as a "mafic-silicic layered intrusion" (MASLI) in part, because, it had already been described as a layered intrusion, but especially because of a thorough manuscript review by T. N. Irvine, who viewed the intrusion as an end-member of a layered intrusion - one fed by highly contrasting magmas rather than just by basalt - and strongly recommended that I frame my description in that context and use a nomenclature consistent with Irvine (1982) (e.g., macrorhythmic layers). MASLI seemed the simplest and most direct name for such a body, and it also seemed appropriate for many of the comparable bodies known at the time.

Pleasant Bay characteristics:

1) It is large in size (12 by 20 km in area and up to 3 km thick) – a scale consistent with many bimodal volcanic systems - e.g., Coso (Bacon and Metz 1984).

2) It is dominated by gabbro and mafic diorite (~ 90 %) with thin layers of felsic cumulates and chilled basaltic pillows, tubes and sheets.

3) Macrorhythmic layers are from a few meters to > 100 meters thick, with chilled basalt at the base (some beginning with several meters of chilled pillows) that grade upward to cumulate gabbro (typically plagioclase + olivine) variably though diorite to monzo-diorite and granite.

4) Fractional crystallization is typically dominant near the base, while hybridization with silicic magna becomes increasingly important upward.

5) The chilled base of a macrorhythmic layer may rest on any lithology from medium-grained gabbro to granite. This demonstrated that the levels of emplacement were not levels of neutral buoyancy, but rheological transitions from strong crystal mush to crystal-poor melt.

6) Silicic layers (and the silicic tops of macrorhythmic layers) commonly consist of a touching framework of blocky to tabular, subhedral plagioclase feldspar, often with lamination and modal layering, indicating that silicic layers are cumulates, not intrusive veins, dikes or sills.

7) The underlying felsic layers have commonly been remobilized by heat from and pressure of the overlying macrorhythmic layer, causing pipes, diapirs, dikes and veins of silicic liquid and crystal mush to penetrate the base of the overlying macrorhythmic layer.

8) Because the pipes are nearly always within ~ 5° of perpendicular to the layers, the layers must have been essentially horizontal when they were emplaced. The present

basin form of the Pleasant Bay intrusion must, therefore, have developed by inward sagging after the layers crystallized.

So, as it was defined, the original MASLI was not a sill complex, but a layered intrusion dominated by mafic input that accumulated as layers at the base of a more silicic magma chamber - i.e., at the rheological boundary between cumulate layers overlying crystal-poor melt. As such, they preserved stratigraphic records of the evolution of periodically replenished silicic magma chambers. Although the layers superficially resembled sills, they were not emplaced into horizontal fractures, and the layers by no means had matching walls as expected in sills and dikes. There was also strong compositional asymmetry within most macrorhythmic layers - with rapid upward variation from basalt to granite near the top of each layer. The typically rapid transitions from mafic to felsic compositions appear to reflect interactions along boundaries between convective cells in the basaltic magma and in the overlying silicic magma (i.e., double diffusive convection).

The Pleasant Bay intrusion is cut sharply by later dikes and sills of fine-grained granite and basalt as well as composite dikes and sills consisting of chilled mafic pillow-like bodies in fine-grained (non-cumulate) granite. In these dikes, whole-rock analyses of basalt typically match closely the compositions of chilled basaltic margins of layers, and granite compositions typically appear to be appropriate for liquids that produced the most evolved felsic cumulates in the MASLI.

Fundamental characteristic features of MASLI

Wiebe and Collins (1998) proposed criteria for recognizing the key process operating in MASLI formed by emplacement of basaltic magma onto a floored silicic magma chamber - i.e. between a lower crystal mush with plastic rheology and an overlying chamber with Newtonian rheology. Both the base and the top of mafic layers emplaced into a more felsic magma chamber have characteristic features that help distinguish a MASLI. The base of mafic input is typically chilled, but the degree of chilling depends on the thermal contrast between resident magma and mafic input, and the base may be highly convolute with prominent convex downward lobes or essentially planar, depending on the strength of the underlying cumulate (Figs. 5a, b, c). Where basalt flows into a silicic chamber above a thick layer (e.g., 10s of meters) of relatively weak crystal mush, the weight and heat content of the mafic layer will typically compact and remobilize the underlying mush, leading to a highly convolute base (Fig. 5d). In this case, it is common to see extensive contamination (hybridization) of the basal chill because thin septa of silicic melt and remobilized crystal mush rise between much thicker mafic fingers during emplacement of the flow (Snyder and Tait 1995, 1998). There, the large surface area and greater volume of mafic magma promotes mixing (Sparks and Marshall 1986). Here also, silicic pipes that develop after emplacement lead to further contamination within a mafic sheet (Fig. 6). Where the compositional and density contrasts between resident crystal mush and a new basaltic injection are small and the underlying weak crystal mush is thin, a planar base typically develops on the basaltic layer and contamination is at a minimum. When a strong, upper chilled margin is established before upwelling felsic magma rises through the chilled base, it is common to find the rejuvenated felsic mush trapped beneath the chilled top (Fig. 7).

If the mafic layer is less than a meter thick and the temperature contrast between resident felsic magma and the mafic magma is great (> 100-200°C), the top of the layer is also typically chilled (Fig. 8). Thicker mafic layers typically lack chilled upper margins, indicating destruction of the expected initial upper chill, probably due to double-diffusive convection (Huppert and Turner 1981) with overlying silicic melt, causing shear at the boundary. The resulting macrorhythmic layer develops a compositional gradation between mafic input and the resident felsic magma. This gradient provides the most direct evidence that the mafic layer was emplaced at a rheological boundary between resident felsic cumulates and crystal-poor silicic melt. These compositional transitions may occur over tens of meters to less than a meter of layer thickness (Fig. 9).

Fluid mechanic experiments and calculations on processes in MASLI

Plutonic evidence for basaltic replenishments into silicic magma chambers inspired some valuable fluid mechanic experiments. Snyder and Tait (1995) and Jellinek and Kerr (1999) showed that a dense and lower viscosity fluid (analogous to basalt) injected into a floored chamber of less dense and higher viscosity (analogous to silicic magma) produced a viscous gravity current that trapped a thin layer of ambient fluid beneath it, and that these injections develop a flow-front instability that forms fingers in the direction of flow. The underlying silicic melt tends to rise buoyantly as thin sheets between the fingers, and Snyder and Tait (1998) addressed the potential for selective contamination of silicic magma by diffusion between the silicic sheets and basalt fingers. The thin felsic sheets between mafic fingers also provide a record of the direction of flow during emplacement of the mafic layers. Snyder (2000) evaluated the thermal effects of basalt injections into a silicic chamber using a parameterized scaling analysis coupled with the thermodynamics of crystallization, providing estimates for the timescale for the start-up of convection, the rates at which basalt cools and silicic magma warms and the life-span of a thermal gradient in silicic magma.

Mafic-felsic sill complexes (?)

Recently, several intrusions that superficially appear comparable to MASLI have been described as sill complexes. Is a mafic-felsic sill complex distinct from a MASLI, or have the same field relations been interpreted differently? It is not uncommon for dikes and sills to occur within MASLI, but they are easily recognized because both margins are strongly chilled, matching and locally sharply cross-cut macrorhythmic layers. So it would seem that a sill complex in which sills are emplaced at random levels should be easily distinguished from a MASLI.

Two intrusions with interlayered mafic and felsic rocks occur near the crest of the Sierra Nevada range: the Aberdeen complex (Coleman et al. 1995) and the mafic intrusive complex of Onion Valley (Sisson et al. 1996). Both contain prominent portions that consist of chilled meter-scale mafic sheets separated by coarser-grained, thin, more felsic septa. In both papers the chilled mafic layers are termed sills, presumably meaning the layers may have been emplaced at random levels and do not form a stratigraphic sequence. Although Coleman et al. (1995) provided little information on field relations, the description provided by Sisson et al. (1996) is extensive, clear and well documented.

Intrusive episode two of the Onion Valley "sill swarm" (Sisson et al. 1996) has: (1) a lower section of sills in which chills are observed every 2 to 4 meters, with felsic inter-sill septa usually missing, but locally present, (2) a 200 meter thick middle section of mafic cumulates and (3) an upper section of thin (0.1-1.5 m) chilled basaltic layers separated by thin (a few mm to 15 cm thick) felsic layers that consisted of felsic crystal mush with interstitial liquid. Sisson et al. (1996) suggest the chilled mafic sills formed by the ascent of dikes that "may have been arrested by a density interface between crystal mush, now preserved as inter-sill septa, and higher, melt-rich magma" (Sisson et al. 1996, p. 85). Emplacement of basalt at the interface between felsic crystal mush and melt-rich magma is what marks emplacement in a MASLI, but because the felsic crystal mush is likely to be less dense than the basalt, the effect may be due to the contrast in rheology of the crystal mush and the melt rather than density.

Elsewhere, however, on page 86 they also state "Many injections of mafic magma failed to reach the density interface and instead spread laterally between earlier sills along zones occupied by trapped crystal mush". Here the levels of emplacement would be felsic septa that are likely to retain liquid long after the adjacent basaltic layers are solid. How could we distinguish emplacement here from that of a MASLI? Assuming that a new basaltic injection is emplaced within a felsic crystal mush septum (layer) between two older and likely solid basaltic layers, there would seem to be a high probability that, at some point in the emplacement, the solid basaltic layers would fracture, permitting the new basalt "sill" to send apophyses into those fractures. It would be interesting to know if there are examples of basaltic layers feeding apophyses into fractures within adjacent mafic layers.

Recent work on the Cordillera del Paine pluton of southern Chile and particularly on the mafic sill complex that lies within the Torres del Paine granite (Leuthold et al. 2014 and references therein) provides new insights into the origin of this complex. The sub-horizontal mafic complex is about 250 meters thick with lower gabbro and upper gabbro units and an overlying monzodiorite unit beneath the main granite body, and occurs at elevations between 1000 and 1300 meters. Recent high-precision U-Pb zircon dates of layers within the mafic complex (Leuthold et al. 2012) indicate that these mafic layers decrease in age upward from the base to the top (12.472 to 12.431 Ma), consistent with younging upward expected in a MASLI. However, all of the reported ages of granite at higher and lower elevations are older than any rocks in the mafic complex, and from the roof downward, the granites decrease in age (Michel et al. 2008). While the ages of the mafic layers are younger than the youngest dated granite sample (12.49 Ma), one granite sample was taken about 700 meters higher than the top of the mafic complex and another more than one km to the west at about the same elevation as the mafic complex. Considering the distances between the dated samples and the small differences in the ages (12.47 vs. 12.49 Ma), it seems possible that granites as young as 12.47 Ma exist both above and below the mafic complex.

Many layers in the mafic complex show a strong compositional asymmetry and complex relations with the irregular underlying felsic layers. Figure 3b in Leuthold et al. (2012) shows two mafic layers (~ 6 to 10 meters thick) in the lower hornblende gabbro that show the same asymmetry, with mafic enclaves distributed in the lower part of the felsic top. Apparently an original chilled top of each layer was broken up and the transition between lower basalt and upper felsic material in each layer now appears gradational. The chilled base of the second layer has roughly 3 to 4 meter wavelengths of downward projecting lobes, which suggests a comparable thickness of crystal mush over which the basalt flowed - much like Bain et al. (2013) show for layers in the Pleasant Bay intrusion. More leucocratic felsic material (probably filter-pressed interstitial liquid) project upward as flame structures between the lobes. Since mafic layers are basally chilled at most levels, it seems likely that all were emplaced within a cooler chamber.

In the upper gabbro unit, Leuthold et al. (2014) indicate the layers grade upward from olivine gabbro to finer-grained monzodiorite at the top. In the overlying monzodiorite unit, the lower monzodiorite layers grade upward to more leucocratic rocks with scarce porphyritic K-feldspar and quartz, while in the upper part of the unit, monzodiorite occurs as ~ 1-meter thick tabular enclaves in porphyritic granite immediately beneath overlying granite. The rapid compositional variation from gabbro to more evolved and leucocratic rocks resembles compositional variation in MASLI macrorhythmic layers (Fig. 9) and suggests that the mafic “sills” were emplaced as intramagmatic lava flows into a more silicic magma chamber which developed strong compositional variation at the base of the chamber due to crystal fractionation of gabbro and mixing with more evolved resident magma at the base of the chamber – an interpretation much like Michael (1991) proposed.

Reinterpretations of previously studied MASLI

Two recent papers take very different approaches to two previously studied interlayered mafic-silicic systems. Padwardhan and Marsh (2011) restudied the Isle au

Haut intrusion (Chapman and Rhodes 1992) and offer a totally new interpretation based on the assumption that a steep basalt feeder invaded a partly crystallized homogeneous massive diorite and spread all of the gabbroic layers at the same time rather than sequentially on an aggrading floor of a dioritic magma chamber. There seems to be no objective field evidence for this interpretation. The dioritic rocks are not homogeneous but are increasingly fractionated in the higher layers and likely grade upward to an overlying granite body. There is no evidence for a vertical body of gabbro (basalt) feeding multiple sheets of gabbro at the same time as shown in the first three panels of their Fig. 23. These diagrams closely resemble Figure 14 in Marsh (1995), which illustrates a hypothetical mush melt column beneath a volcano like Kilauea. The authors apparently reject the existence of a magma chamber floor or crystal fractionation of the diorite. The basal chilled margins of the gabbroic layers indicate basalt was emplaced as crystal-poor melt, solidified rapidly, and sank downward in lobes with wavelengths on the order of a few meters, suggesting comparable depths of crystal mush. These relations indicate that the gabbro layer was more dense than the dioritic crystal mush beneath it. Hence, lateral emplacement of basalt into homogeneous diorite seems most unlikely.

Some workers have continued to hypothesize that the thin silicic layers were injected into homogeneous, incompletely crystallized gabbro – essentially a return to the original concept of “net-veining” in 1950s and early 1960s, a model that fails completely on thermal grounds. Shortland et al. (1996) suggested this for the Elizabeth Castle igneous complex, Jersey, Channel Islands. Caroff et al. (2011) revisited portions of two different mafic-felsic complexes: Northern Guernsey, Channel Islands and Saint-Jean-du-Doigt, France. The overall model that these authors present for both complexes is emplacement of silicic magma as thin sheets within previously emplaced gabbro, rather than the emplacement of basaltic magma into a felsic chamber. They, in some cases, deny that the mafic sheets have chilled margins, but having visited both of these complexes, I feel sure they exist. In any event, it seems mechanically and thermally impossible to inject small amounts of rhyolite into partly crystallized basalt and keep the rhyolite from becoming superheated and mix into the basalt. Barboni et al. (2008) recognized the features in the Saint-Jean-du-Doigt to be consistent with a MASLI (M. Barboni, personal communication 2014).

Known occurrences of mafic-silicic layered intrusions

Interlayered mafic and felsic rocks in which basaltic magma likely flowed onto the floor of a silicic magma chamber occur widely (Table 1). Examples range in age from Tertiary to Paleo-Proterozoic and from arc to extensional terranes on all continents as well as in Greenland, New Zealand, Japan and Iceland. Those in extensional terranes were typically fed by highly contrasted mafic and silicic magmas (tholeiite basalt and leucogranite) (e.g., the Pleasant Bay intrusion, Mount Hay and Austerhorn). Those in arc settings typically have a wider range of mafic and intermediate magma feeding a silicic chamber (e.g. Cordillera del Paine, Tuross Head pluton and Ingonish).

Implications

Because the characteristic features of macrorhythmic layers within MASLI are distinctive and robust, they can be recognized even in strongly deformed and metamorphosed terranes. Hence, the same petrologic insights may readily be extracted from them there. The mafic-felsic rocks of Mt. Hay in central Australia provide one example of this. Earlier work (Collins and Sawyer 1996) had interpreted these 1800 Ma mafic granulite facies rocks interlayered with coarse-grained granitic rocks (metamorphosed at about 8 kb) as a record of pervasive transfer of granitic magma through the lower-middle crust. In revisiting these rocks, Bonnay et al. (2000) recognized that the mafic layers typically had one very fine-grained mafic margin with convex outward lobes against coarse-grained granite and that the mafic layers coarsened and became more felsic toward the other boundary with granite, often containing large alkali-feldspars comparable to those within the granitic layers (Fig. 10). These features indicated that the mafic granulites were likely basaltic liquids that were emplaced onto granitic crystal mush and partially mixed with overlying contemporaneous granitic magma. Further, the mafic granulite layers had compositions consistent with crystallization of olivine tholeiite at 1 to 2 kb (Bonnay et al. 2000). So the mafic-felsic layers originally crystallized at a shallow depth long before deformation and metamorphism and provided no information on magma transfer in the deep crust. Of added value were the robust way-up indicators, which are capable of aiding structural interpretations. Here, these way-up indicators that were consistent with the upright and overturned limbs of a large, steep sheath fold.

Mafic-silicic layered intrusions are fed multiple times by both mafic and silicic magmas and provide exceptional opportunities for recognizing and sampling rocks, which closely approximate liquids in a plutonic setting. Stratigraphic sequences of basally chilled mafic sheets have the potential to provide information on liquid compositions that feed the intrusion through time, though care must be taken to avoid contamination from the adjacent silicic magma. Fortunately, the same basaltic liquids can typically be sampled in cross-cutting dikes that likely fed higher levels of the intrusion, though without a stratigraphic control on relative age. New injections of granite (typically very fine-grained dikes up to 20 meters thick) can be readily sampled and their compositions usually appear to be appropriate for melts that produced the most evolved silicic cumulate layers. It is common for a silicic chamber to trap more than one type of mafic to intermediate magma (e.g., Wiebe 1974a,b, Kolker and Lindsley 1989). The compositions of chilled margins of basaltic layers may vary up-section in MgO (sometimes greatly) and vary randomly (Wiebe 1993). This observation provides strong support for the existence of multiple mafic chambers at depth with different degrees of fractionation and hybridization. The overall major element variations of these chills is commonly consistent with a liquid line of descent controlled by phase equilibria, whereas the trace elements are highly scattered probably due to variable fractionation and contamination in different chambers at depth.

Since basaltic magma is more dense than either silicic liquid or crystal mush, the level of emplacement must have occurred within an upward transition from a strong crystal mush with a plastic rheology to a silicic liquid with Newtonian rheology. Emplacement of basalt at this level demonstrates the existence of a silicic magma chamber and has the potential to provide information on its size. The lateral extent of mafic sheets provides a rough estimate of the lateral extent of the silicic chamber at the time of the influx, and the common association of extensive sheets of stoped country rock blocks with the mafic sheets indicates the contemporary existence of an overlying silicic magma with Newtonian rheology beneath a roof of either country rock or solid granite (Hawkins and Wiebe 2004). With knowledge of the chamber extent, the thermal impact of the mafic input on crystals (e.g., quartz) in the felsic magma and the characteristic thickness (volume) of basaltic layers emplaced can yield an estimate of the height (and, hence, the volume) of a silicic magma chamber (Wiebe and Hawkins 2015).

Basaltic injections into silicic chambers can also provide insights into how solidification of the silicic chamber occurs. The common occurrence of extensive layers of coarse-grained granite, in some cases many meters thick, between basally chilled mafic sheets indicates that felsic crystal mush was extensively deposited on the floor of the chamber during the time between two sequential mafic injections. Deformations that occur along the contact between an overlying basally chilled mafic layer and underlying granite can also provide insights into the rheology of the underlying granite (Bain et al. 2013).

A mafic-silicic layered intrusion contains a stratigraphic sequence that records magma chamber processes and events that probably have a time scale comparable to that of a volcanic stratigraphy. In situations where coeval volcanic rocks are exposed (e.g., Miocene volcano-plutonic systems, southern Nevada - Miller et al. 2005), a MASLI offers the possibility of correlating volcanic and plutonic rocks, processes and events as well as comparing the compositions of liquids that fed a magma chamber with material that erupted from it. Whole rock and mineral compositions as well as mineral zoning could yield new insights into links between magma chamber processes and events. The high temporal resolution now possible with U-Th zircon dating (e.g., Leuthold et al. 2012) may, for example, permit recognizing whether the trigger of a specific volcanic event was related to the end of a long period of mafic input or to a significant input of silicic magma.

Acknowledgements: I've benefitted greatly from conversations in the field with many colleagues over the years. I particularly want to thank Tony Morse, Don Snyder, David Hawkins, Mark Jellinek, John Eichelberger and Calvin Miller. Helpful reviews by Sheila Seaman and Sandra Barr improved the paper.

References cited

Akaad, M.K. (1956) The Ardara granitic diapir of County Donegal, Ireland. Quarterly Journal of the Geological Society of London, 112, 263-290.

Asrat, A., Barbey, P., Ludden, J.N., Reisberg, L., Gleizes, G., and Ayalew, D. (2004) Petrology and isotopic geochemistry of the Pan-African Negash pluton, northern Ethiopia: Mafic-felsic magma interactions during the construction of shallow-level calc-alkaline plutons. Journal of Petrology, 45, 1147-1179.

Ayuso, R.A., and Arth, J.G. (1997) The Spruce Head composite pluton: An example of mafic to silicic Salinian magmatism, coastal Maine, northern Appalachians. In Sinha, A.K., Whalen, J.B., and Hogan, J.P., The Nature of Magmatism in the Appalachian Orogen, Geological Society of America Memoir 191, 19-43.

Bachl, C.A., Miller, C.F., Miller, J.S., and Faulds, J.E. (2001) Construction of a pluton: Evidence from an exposed cross-section of the Searchlight pluton, Eldorado Mountains, Nevada. Geological Society of America Bulletin, 113, 1213-1228.

Bacon, C.R., and Druitt, T.H. (1988) Compositional evolution of the zoned calcalkaline magma chamber of Mount Mazama, Crater Lake, Oregon. Contributions to Mineralogy and Petrology, 98, 224-256.

Bacon, C.R., and Metz, J. (1984) Magmatic inclusions in rhyolites, contaminated basalts, and compositional zonation beneath the Coso volcanic field, California. Contributions to Mineralogy and Petrology, 85, 346-365.

Bailey, E.B., and McCallien, W.J. (1956) Composite minor intrusions, and the Slieve Gullion complex, Ireland. Liverpool and Manchester Geological Journal, 1, 466-503.

Bailey, E.B., and Thomas, H.H. (1930) The geology of Ardnamurchan, north-west Mull and Coll. Memoirs of the Geological Survey of the United Kingdom, 393 p.

Bain, A.A., Jellinek, A.M., and Wiebe, R.A. (2013) Quantitiative field constraints on the dynamics of silicic magma chamber rejuvenation and overturn. Contributions to Mineralogy and Petrology, 165, 1275-1294.

Barbarin, B. (1988) Field evidence for successive mixing and mingling between the Poilard diorite and the Saint-Julien-la-Vetre monzogranite (Nord-Forez, Massif Central, France). Canadian Journal of Earth Science, 25, 49-59.

Barboni, M., Bussy, F., Schoene, B., and Schaltegger, U. (2008) Architecture and emplacement mechanism of the Saint Jean du Doigt bimodal intrusion, Brittany, France. In Geophysical Research Abstracts (Vol. 10).

Bickford, M.E. (1963) Petrology and structure of layered gabbro Pleasant Bay, Maine. The Journal of Geology, 71, 215-237.

Bishop, A.C. (1964) Dark margins at igneous contacts. A critical study with special reference to those in Jersey, C.I. (1964) Proceedings of the Geologists' Association, 74, 289-300.

Blake, D.H. (1966) The net-veined complex of the Austurhorn intrusion, southeastern Iceland. Journal of Geology, 74, 891-907.

Blake, D.H., Elwell, R.W.D., Gibson, I.L., Skelhorn, R.R., and Walker, G.P.L. (1965) Some relationships resulting from the intimate association of acid and basic magmas. Quarterly Journal of the Geological Society of London 121, 31-49.

Blake, D.H., and Hoatson, D.M. (1993) Granite, gabbro, and migmatite field relationships in the Proterozoic Lamboo complex of the East Kimberley region, Western Australia. Australian Geological Survey Organisation Journal of Australian Geology and Geophysics, 14, 319-330.

Blundy, J.D., and Sparks, R.S.J. (1992) Petrogenesis of mafic inclusions in granitoids of the Adamello Massif, Italy. Journal of Petrology, 33, 1039-1104.

Bonnay, M., Collins, W.J, Sawyer, E.W., and Wiebe, R.A. (2000) Mt. Hay: granite magma transfer through the deep crust or a buried high-level plutonic complex? In: Collins, W.J. (ed) Granite magma segregation and transfer during compressional deformation in the deep crust? Proterozoic Arunta Inlier, central Australia. Field Guide FA4, Geological Society of Australia Incorporated. P. 8-46.

Brown, P.E., and Becker, S.M. (1986) Fractionation, hybridisation and magma-mixing in the Kialineq centre East Greenland. Contributions to Mineralogy and Petrology, 92, 57-70.

Buddington, A.F. (1959) Granite emplacement with special reference to North America. Geological Society of America Bulletin, 70, 671-747.

Caroff, M., Coint, N., Hallot, F., Hamelin, C., Peucat, J-J., and Charreteur, G. (2011) The mafic-silicic layered intrusions of (France) and north Guernsey (Channel Islands), Armorican massif: Gabbro-diorite layering and mafic cumulate-pegmatoid association. Lithos, 125, 675-692.

Castro, A., De la Rosa, J.D., Fernandez, C., and Moreno-Ventas, I. (1995) Unstable flow, magma mixing and magma-rock deformation in a deep-seated conduit: the Gil-Marquez Complex, south-west Spain. Geologische Rundschau, 84, 359-374.

Chapman, C.A. (1962) Diabase-granite composite dikes, with pillow-like structure, Mount Desert Island, Maine. The Journal of Geology, 70, 529-564.

Chapman, M., and Rhodes, J.M. (1992) Composite layering in the Isle au Haut igneous complex, Maine. Journal of Volcanology and Geothermal Research, 51, 41-60.

Chappell, B.W. (1997) Compositional variation within granite suites of the Lachlan Fold Belt: its causes and implications for the physical state of granite magma. Transactions of the Royal Society of Edinburgh: Earth Sciences, 88, 159-180.

Chappell, B.W., White, A.J.R., and Wyborn, D. (1987) The importance of residual source material (restite) in granite petrogenesis. Journal of Petrology, 28, 1111-1138.

Christiansen, R.L. (1979) Cooling units and composite sheets in relation to caldera structure. In: C.E. Chapin and W.E. Elston (eds) Ash-flow tuffs. Geological Society of America Special Paper 180, 29-42.

Clark, S., Spera, F.J., and Yuen, D.A. (1987) Steady state double-diffusive convection in magma chambers heated from below. In: Mysen, B. O. (ed.) Magmatic Processes: Physicochemical Principles. Geochemical Society Special Publication 1, 289-305.

Clemens, J.D., and Mawer, C.K. (1992) Granitic magma transport by fracture propagation. Tectonophysics, 294, 339-360.

Coleman, D.S., Glazner, A.F., Miller, J.S., Bradfored, K.J., Frost, T.P., Joye, J.L., and Bachl, C.A. (1995) Exposure of a Late Cretaceous layered mafic-felsic system in the central Sierra Nevada batholith, California. Contributions to Mineralogy and Petrology, 120, 129-136.

Collins, W.J., and Sawyer. E.W. (1996) Pervasive granitoid magma transfer through the lower-middle crust during non-coaxial compressional deformation. Journal of Metmorphic Geology. 14, 565-579.

Collins, W.J., Wiebe, R.A., Healy, B. and Richards, S.W. (2006) Replenishment, crystal accumulation and floor aggradation in the megacrystic Kameruka Suite, Australia. Journal of Petrology, 47, 2073-2104.

Compton, R.R. (1955) Trondhjemite batholith near Bidwell Bar, California. Bulletin of the Geological Society of America, 66, 9-44.

Cook, N.D.J. (1988) Diorites and associated rocks in the Anglem Complex at The Neck, northeastern Stewart Island, New Zealand: an example of magma mingling. Lithos, 21, 247-262.

Currie, K.L. (2003) Emplacement of the Fogo Island batholith, Newfoundland. Atlantic Geology, 39, 79-96.

Davis, G.A. (1963) Structure and mode of emplacement of Caribou Mountain pluton, Klamath Mountains, Caliifornia. Bulletin of the Geological Society of America, 74, 331-348.

de Waard, D. (1976) Anorthosite-adamellite-troctolite layering in the Barth Island structure of the Nain complex, Labrador. Lithos 9, 293-308.

Eichelberger, J.C. (1978) Andesitic volcanism and crystal evolution. Nature, 275, 21-27.

Eichelberger, J.C. and Gooley, R. (1977) Evolution of silicic magma chambers and their relationship to basaltic volcanism. The Earth's Crust, 57-77.

Eichelberger, J.C., Chertkoff, G.D., Dreher, S.T., and Nye, C.J. (2000) Magmas in collision: Rethinking chemical zonation in silicic magmas. Geology, 28, 603-606.

Elwell, R.W.D. (1958) Granophyre and hybrid pipes in a dolerite layer of Slieve Gullion. The Journal of Geology, 66, 57-71.

Elwell, R.W.D., Skelhorn, R.R., and Drysdall, A.R. (1960) Inclined granitic pipes in the diorites of Guernsey. Geological Magazine, 97, 89-105.

Elwell, R.W.D., Skelhorn, R.R., and Drysdall, A.R. (1962) Net-veining in the diorite of northeast Guernsey, Channel Islands. The Journal of Geology, 70, 215-226.

Fernandez, A.N., and Gasquet, D.R. (1994) Relative rheological evolution of chemically contrasted coeval magmas: example of the Tichka plutonic complex (Morocco). Contributions to Mineralogy and Petrology, 116, 316-326.

Franceschelli, M., Puxeddu, M., Cruciani, G., Dini, A., and Loi, M. (2005) Layered amphibolite sequence in NE Sardinia, Italy: remnant of a pre-Variscan mafic-silicic layered intrusion? Contributions to Mineralogy and Petrology, 149, 164-180.

Furman, T., Meyer, P.S., and Frey, F. (1992a) Evolution of Icelandic central volcanoes: evidence from the Austurhorn intrusion, southeastern Iceland. Bulletin of Volcanology, 55, 45-62.

Furman, T., Frey, F., and Meyer, P.S. (1992b) Petrogenesis of evolved basalts and rhyolites at Austurhorn, southeastern Iceland: the role of fractional crystallization. Journal of Petrology, 33, 1405-1445.

Gamble, J.A. (1979) Some relationships between coexisting granitic and basaltic magmas and the genesis of hybrid rocks in the Tertiary central complex of Slieve Gullion, northeast Ireland. Journal of Volcanology and Geothermal Research, 5, 297-316.

Gibson, I.L., and Walker, G.P.L. (1964) Some composite rhyolite/basalt lavas and related composite dykes in eastern Iceland, Proceedings of the Geologists' Association. 74, 301-318.

Gunn, B.M., and Watkins, N.D, (1969) The petrochemical effect of the simultaneous cooling of adjoining basaltic and rhyolitic magmas. Geochimica et Cosmochimica Acta, 33, 341-356.

Harker, A. (1904) The Tertiary igneous rocks of Skye. Memoirs of the Geological Survey of the United Kingdom, 476 p.

Harper, B.E., Miller, C.F, Koteas, G.C., Cates, N.L, Wiebe, R.A., Lazzareschi, D.S., and Cribb, J.W. (2004) Granites, dynamic magma chamber processes and pluton construction: the Aztec Wash pluton, Eldorado Mountains, Nevada, USA. Transactions of the Royal Society of Edinburgh: Earth Sciences, 95, 277-295.

Hildreth, W., Halliday, A.N., and Christiansen, R.L. (1991) Isotopic and chemical evidence concerning the genesis and contamination of basaltic and rhyolitic magma beneath the Yellowstone Plateau volcanic field. Journal of Petrology, 32, 63-138.

Hildreth, W., and Wilson, C.J.N. (2007) Compositional zoning of the Bishop Tuff. Journal of Petrology, 48, 951-999.

Hill, M., and Abbott, R.N. (1989) Commingled gabbroic and granitic magmas in the northern Bays-of-Maine igneous complex, Calais area, Maine. InTucker, R.D. and Marvinney, R.G. (eds) Studies in Maine Geology – Igneous and metamorphic geology, 4, 35-43.

Huppert, H.E., and Sparks, R.S.J. (1984) Double-diffusive convection due to crystallization in magmas. Annual Review of Earth and Planetary Sciences, 12, 11-37.

Huppert, H.E., and Turner, J.S. (1981) Double-diffusive convection. Journal of Fluid Mechanics, 106, 299-329.

Hutton, D.H.W., and Siegesmund, S. (2001) The Ardara granite: reinflating the balloon hypothesis. Zeitschrift der Deutschen Geologischen Gesellschaft, 309-323.

Irvine, T.N. (1982) Terminology for layered intrusions. Journal of Petrology, 23, 127-162.

Ishihara, S., Yoshikura, S., Sato, H., Satake, Y., and Atsuta, S. (2003) Ilmenite-series pink and gray granitoids and felsic/mafic magma interaction across the late

Cretaceous Inner Zone Batholith of SW Japan. Hutton Symposium V, Field Guidebook. Geological Survey of Japan, Interim-Report no.28, 41-60.

Janousek, V., Braithwaite, C.J.R., Bowes, D.R., and Gerdes, A. (2004) Magma-mixing in the genesis of Hercynian calc-alkaline granitoids: an integrated petrographic and geochemical study of the Savaza intrusion, central Bohemian pluton, Czech Republic. Lithos, 78, 67-99.

Jellinek, A.M., and Kerr, R.C. (1999). Mixing and compositional stratification produced by natural convection 2. Applications to the differentiation of basaltic and silicic magma chambers and komatiite lava flows. Journal of Geophysical Research, 104, No. B4, 7203-7218.

Judd, J.W. (1893) On the composite dykes of Arran. Quarterly Journal of the Geological Society of London, 49, 536-565.

Kamiyama, H., Nakajima, T., and Kamioka, H. (2007) Magmatic stratigraphy of the tilted Tottabesu plutonic complex, Hokkaido, north Japan. The Journal of Geology, 115, 295-314.

Kolker, A., and Lindsley, D.H. (1989) Geochemical evolution of the Maloin Ranch pluton, Laramie anorthosite complex, Wyoming: Petrology and mixing relations. American Mineralogist, 74, 307-324.

Leuthold, J., Muntener, O., Baumgartner, L.P., Putlitz, B., Ovtcharova, M., and Schaltegger, U. (2012) Time resolved construction of a bimodal laccolith (Torres del Paine, Patagonia). Earth and Planetary Science Letters, 325-326, 85-92.

Leuthold, J., Muntener, O., Baumgartner, L.P., Putlitz, B., and Chiaradia, M. (2013) A detailed geochemical study of a shallow arc-related laccolith: the Torres del Paine mafic complex (Patagonia). Journal of Petrology, 54, 273-303.

Leuthold, J., Muntener, O., Baumgartner, L.P., and Putlitz, B. (2014) Petrological constraints on the recycling of mafic crystal mushes and intrusions of braided sills in the Torres del Paine mafic complex (Patagonia). Journal of Petrology, 55, 917-949.

Lindline, J., Crawford, W.A., and Crawford, M.L. (2004) A bimodal volcanic-plutonic system: the Zarembo Island extrusive suite and the Burnett Inlet intrusive complex. Canadian Journal of Earth Sciences, 41, 355-375;

Lipman, P.W., Christiansen, R.L., and O’Connor, J.T. (1966) A compositionally zoned ash-flow sheet in southern Nevada. United States Geological Survey Professional Paper 524-F, 47 p.

MacColl, R.S. (1964) Geochemical and structural studies in batholithic rocks of southern California: Part 1, Structural Geology of the Rattlesnake Mountain pluton. Geological Society of America Bulletin, 75, 805-822.

Mattson, S.R., Vogel, T.A., and Wilband, J.T. (1986) Petrochemistry of the silicic-mafic complexes at Vesturhorn and Austurhorn, Iceland: Evidence for zoned/stratified magma. Journal of Volcanology and Geothermal Research, 28, 197-223.

McMillan, N.J., and McLemore, V.T. (2004) Cambrian-Ordovician magmatism and extension in New Mexico and Colorado. New Mexico Bureau of Geology and Mineral Resources, Bulletin 160, 1-11.

Michael, P.J. (1991) Intrusion of basaltic magma into a crystallizing granitic chamber: The Cordillera del Paine pluton in southern Chile. Contributions to Mineralogy and Petrology, 108, 396-418.

Michel, J., Baumgartner, L., Putlitz, B., Schaltegger, U., and Ovtcharova, M. (2008) Incremental growth of the Patagonian Torres del Paine laccolith over 90 ky. Geology, 36, 459-465.

Miller, C.F., Miller, J.S., and Faulds, J.E. (2005) Miocene volcano-plutonic systems, southern Nevada: a window into upper crustal magmatic processes. In: Stevens, C., Cooper, C. (Eds.), Western Great Basin Geology: Fieldtrip Guidebook and Volume. In: GSA Cordilleran Section, 99, 37–66.

Padwardhan, K., and Marsh, B.D. (2011) Dynamics of the development of the Isla au Haut gabbro-diorite layered complex: Quantitative implications for mafic-silicic magma interactions. Journal of Petrology, 52, 2365-2395.

Paterson, S.R., and Fowler, T.K. (1993) Extensional pluton-emplacement models: do they work for large plutonic complexes? Geology, 21, 781-784.

Paterson, S.R., and Vernon, R.H. (1995) Bursting the bubble of ballooning plutons: A return to nested diapirs emplaced by multiple processes. Geological Society of America Bulletin, 107, 1356-1380.

Patrick, D.W. and, Miller, C.F. (1997). Processes in a composite, recharging magma chamber: evidence from magmatic structures in the Aztec Wash pluton, Nevada. Proceedings of the 30th International Geological Congress, 15, 121-135.

Perugini, D., Poli, G., and Rocchi, S. (2005) Development of viscous fingering between mafic and felsic magmas: evidence from the Terra Nova intrusive complex. Mineralogy and Petrology, 83, 151-166.

Petford, N., Cruden, A.R., McCaffrey, K.J.W., and Vigneresse, J.-L. (2000) Granite magma formation, transport and emplacement in the Earth's crust. Nature, 408, 669-673.

Pietranik, A., and Koepke, J. (2009) Interactions between dioritic and granodioritic magmas in mingling zones: plagioclase record of mixing, mingling and subolidus interactions in the Gesiniec intrusion, NE Bohemian Massif, SW Poland. Contributions to Mineralogy and Petrology, 158, 17-36.

Piwinskii, A.J., and Wyllie, P.J. (1968) Experimental studies of igneous rock series: a zoned pluton in the Wallowa batholith, Oregon. The Journal of Geology, 76, 205-234.

Putirka, K.D., Canchola, J., Rash, J., Smith O., Torrez, G., Patterson, S.R., and Ducea, M.N. (2014) Pluton assembly and the genesis of grantitic magmas: Insights from the GIC pluton in cross section, Sierra Nevada batholith, California, American Mineralogist, 99, 1284-1303.

Ratajeski, K., Glazner, A.F., and Miller, B.V. (2001) Geological Society of America Bulletin, 113, 1486-1502.

Renna, M.R., Tribuzio, R., and Tiepolo, M. (2006) Interaction between basic and acid magmas during the latest stages of the post-collisional Variscan evolution: Clues from the gabbro-granite association of Ota (Corsic-Sardinia batholith). Lithos, 90, 92-110.

Reynolds, D.L. (1941) A gabbro-granodiorite contact in the Slieve Gullion area and its bearing on Tertiary petrogenesis. Quarterly Journal of the Geological Society of London, 97, 1-38.

Reynolds, D.L. (1951) The geology of the Slieve Gullion, Foughill and Carrickarnan: an actualistic interpretation of a Tertiary gabbro-granophyre complex. Transactions of the Royal Society of Edinburgh, 62, 85-142.

Reynolds, D.L. (1953) Comments on an article by Professor L. R. Wager and Sir Edward Bailey entitled “Basic magma chilled against acid magma”. Nature, 172, 69-70.

Reynolds, D.L. (1961) Lapies and solution pits in olivine-dolerite sills at Slieve Gullion, Northern Ireland. The Journal of Geology. 69, 119-117.

Richey, J. (1937) Discussion of a paper by D. L. Reynolds entitled “Contact phenomena indicating a Tertiary age for the gabbros of the Slieve Gullion district”. Proceedings of the Geologists’ Association, 48, 247-275.

Richey, J.E., and Thomas, H.H. (1932) The Tertiary ring complex of Slieve Gullion (Ireland). Quarterly Journal of the Geological Society of London, 88, 776-849.

Seaman, S.J., Scherer, E.E., Wobus, R.A., Zimmer, J.H.. and Sales, J.G. (1999) Late Silurian volcanism in coastal Maine: The Cranberry Island series. Bulletin of the Geological Society of America, 111, 686-708.

Shortland, R.A, Salmon, S., Rowbotham, G., and Regan, P.F. (1996) Coexisting acid and basic magmas of the Elizabeth Castle igneous complex, Jersey, Channel Islands. Proceedings of the Ussher Society, 9, 121-126.

Sigurdsson H. and Sparks, R.S.J. (1981) Petrology of rhyolitic and mixed magma ejecta from the 1875 eruption of Askja, Iceland. Journal of Petrology, 22, 41-84.

Sisson, T.W., Grove, T.L., and Coleman, D.S. (1996) Hornblende gabbro sill complex at Onion Valley, California, and a mixing origin for the Sierra Nevada batholith. Contributions to Mineralogy and Petrology, 126, 81-108.

Skelhorn, R.R., and Elwell, R.W.D. (1966) The structure and form of the granophyric quartz-dolerite intrusion, Centre II, Ardnamurchan, Argyllshire. Transactions of the Royal Society of Edinburgh, 66, 285-308.

Snyder, D. (2000) Thermal effects of the intrusion of basaltic magma into a more silicic magma chamber and implications for eruption triggering. Earth and Planetary Science Letters, 175, 257-273.

Snyder, D., and Tait, S. (1995) Replenishments of magma chambers: comparison of fluid-mechanic experiments with field relations. Contributions to Mineralogy and Petrology, 122, 230-240.

Snyder, D., and Tait, S. (1998) The imprint of basalt on the geochemistry of silicic magmas. Earth and Planetary Science Letters, 160, 433-445.

Snyder, D., Crambes, C., Tait, S., and Wiebe, R.A. (1997) Magma mingling in dikes and sills. The Journal of Geology, 105, 75-86.

Sparks, R.S.J., and Huppert, H.E. (1984) Density changes during fractional crystallization of basaltic magmas: fluid dynamic implications. Contributions to Mineralogy and Petrology, 85, 300-9.

Sparks, R.S.J., and Marshall, L. (1986) Thermal and mechanical constraints on mixing between mafic and silicic magmas. Journal of Volcanology and Geothermal Research, 29, 99-124.

Sylvester, A.G. (1998) Magma mixing, structure, and re-evaluation of the emplacement mechanism of the Vradel pluton, central Telemark, southern Norway. Norsk Geologisk Tidsskrift, 78, 259-276.

Topley, C.G., Brown, M., D'Lemos, R.S., Power, G.M., and Roach, R.A. (1990) The Northern Igneous Complex of Guernsey, Channel Islands. In D'Lemos, R.S., Stracham, R.A., and Topley, C.G. (eds) The Cadomian Orogeny, Geological Society Speccial Publication No. 51, 245-259.

Turnbull, R., Weaver, S., Tulloch, A., Cole, J., Handler, M., and Ireland, T. (2010) Field and geochemical constraints on mafic-felsic interactions, and processes in high-level arc magma chambers: an example from the Halfmoon pluton, New Zealand. Journal of Petrology, 51, 1477-1505.

Turner, J.S. (1984) Some effects of viscosity on the dynamics of replenished magma chambers. Journal of Geophysical Research 89, 6857-77.

Vasek, R.W., and Kolker, A. (1999) Virginia Dale intrusion, Colorado and Wyoming: magma-mixing and hybridization in a Proterozoic composite intrusion. Rocky Mountain Geology, 34, 195-222.

Vernon, R.H. (1984) Microgranitoid enclaves in granites – globules of hybrid magma quenched in a plutonic environment. Nature, 309, 438-439.

Vogel, T.A., and Walker, B.M. (1975) The Tichka Massif, Morocco – an example of contemporaneous acidic and basic plutonism. Lithos, 8, 29-38.

Vogel, T.A., and Wilband, J.T. (1978) Coexisting acidic and basic melts: Geochemistry of a composite dike. The Journal of Geology, 86, 353-371.

Vogel, T.A., Younker, L.W., Wilband, J.T., and Kampmueller, E. (1984) Magma mixing: the Marsco suite, Isle of Skye, Scotland. Contributions to Mineralogy and Petrology, 86, 231-241.

Wager. L.R., and Bailey, E.B. (1953) Basic magma chilled against acid magma. Nature, 172, 68-69.

Walker Jr., B.A., Miller, C.F., Claiborne, L.L., Wooden, J.L., and Miller, J.S. (2007) Geology and geochronology of the Spirit Mountain batholith, southern Nevada: Implications for timescales and physical processes of batholith construction. Journal of Volcanology and Geothermal Research, 167, 239-262.

Walker, G.P.L., and Skelhorn, R.R. (1966) Some associations of acid and basic igneous rocks. Earth-Science Reviews, 2, 93-109.

Wark, D.A., Hildreth, W., Spear, F.S., Cherniak, D.J., and Watson, E.B. (2007) Pre-eruption recharge of the Bishop magma system. Geology, 35, 235-238.

Weidendorfer, D., Mattsson, H.B., and Ulmer, P. (2014) Dynamics of magma mixing in partially crystallized magma chambers: textural and petrological constraints from the basal complex of the Austurhorn intrusion (SE Iceland). Journal of Petrology, 55, 1865-1903.

Wiebe, R.A. (1973) Relations between coexisting basaltic and granitic magmas in a composite dike. American Journal of Science, 273, 130-151.

Wiebe, R.A. (1974a) Coexisting intermediate and basic magmas, Ingonish, Cape Breton Island. The Journal of Geology, 82, 74-87.

Wiebe, R.A. (1974b) Differentiation in layered diorite intrusions, Ingonish, Nova Scotia. The Journal of Geology, 82, 731-750.

Wiebe, R.A. (1988) Structural and magmatic evolution of a magma chamber: The Newark Island layered intrusion, Nain, Labrador. Journal of Petrology, 29, 383-411.

Wiebe, R.A. (1993) The Pleasant Bay layered gabbro-diorite, coastal Maine: Ponding and crystallization of basaltic injections into a silicic magma chamber. Journal of Petrology, 34, 461-489.

Wiebe, R.A. (1994) Silicic magma chambers as traps for basaltic magmas: The Cadillac Mountain intrusive complex, Mount Desert Island, Maine. The Journal of Geology, 102, 423-437.

Wiebe, R.A., and Hawkins, D.P. (2015) Growth and impact of a mafic-silicic layered intrusion in the Vinalhaven intrusive complex, Maine. Journal of Petrology, 65, 273-298.

Wiebe, R.A., and Collins, W.J. (1998) Depositional features and stratigraphic sections in granitic plutons: implications for the emplacement and crystallization of granitic magma. Journal of Structural Geology, 20, 1273-1289.

Wiebe, R.A., and Wild, T., (1983) Fractional crystallization and magma mixing in the Tigalak layered intrusion, the Nain anorthosite complex, Labrador. Contributions to Mineralogy and Petrology, 84, 327-344.

Wiebe, R.A., Frey, H. and Hawkins, D.P. (2001) Basaltic pillows mounds in the Vinalhaven intrusion, Maine. Journal of Volcanology and Geothermal Research, 107, 171-184.

Wiebe, R.A., Blair, K.D., Hawkins, D.P., and Sabine, C.P. (2002) Mafic injections, in situ hybridization, and crystal accumulation in the Pyramid Peak granite, California. . Geological Society of America Bulletin, 114, 909-920.

Wilcox, R.E. (1944) Rhyolite-basalt complex on Gardiner River, Yellowstone Park. Wyoming. Geological Society of America Bulletin, 55, 1047-1079.

Wilcox, R.E. (1999) The idea of magma mixing: history of a struggle for acceptance. The Journal of Geology, 107, 421-432.

Windley, B.F. (1965) The composite net-veined diorite intrusives of the Julianehab District, South Greenland. Meddelelser om Gronland, 172, no. 8, 1-60.

Xu, X., Dong, C., Li, W., and Zhou, X. (1999) Late Mesozoic intrusive complexes in the coastal area of Fujian, SE China: the significance of the gabbro-diorite-granite association. Lithos, 46, 299-315.

Figures

Figure 1. Field photos of commingled basaltic pillows and granite – features once termed net-vein complexes. **(a)** Vinalhaven intrusive complex. **(b)** Interior of a composite dike that cuts layered gabbro, Vinalhaven. (Photos: R.A. Wiebe)

Figure 2. Two field photos of commingling in Austurhorn, Iceland. **(a)** Thin chilled mafic sheets in granite. **(b)** Chilled base of a thicker basaltic layer resting on hybridized felsic material, that grades downward to the disrupted top of an underlying layer. Note leucogranite upwelling between the mafic lobes. This likely represents filter-pressed interstitial liquid within the hybrid felsic material. (Photos: R.A. Wiebe)

Figure 3. Field photos of field relations in Ingonish intrusion. **(a)** Chilled basaltic layers and pillows separated by thin layers of cumulate diorite. **(b)** Chilled base of a thicker porphyritic basaltic layer resting on hybrid diorite with mafic enclaves. **(c)** Unchilled

top of a thick basaltic layer with enclaves in overlying diorite that decrease upward in size. (Photos: R.A. Wiebe)

Figure 4. Mafic and tonalitic layers in the Val Freda complex, Adamello Massif, Italy. **(a)** The top and bottom of two mafic layers separated by a thin seam of tonalite. The lower mafic layer varies upward from (1) medium-grained mafic core to (2) s more felsic intermediate rock to (3) a strongly chilled upper margin into which dark flame structures project (arrows). These are likely formed during upward movement of H_2O as the interior of the layer crystallized. White circle is a coin about 2 cm in diameter. 4 is a thin tonalite seam, and 5 the overlying mafic layer. **(b)** This photo was taken about 2 meters to the right of (a) and shows all of the lower layer in (a), the underlying tonalite seam, and mafic layer layer below that (note prominent tonalitic diaper). The numbers on the photo match those in (a) with the upward compositional gradation (1 and 2) and the strong upper chill of that layer (3). The upper tonalite (4) is not labeled; it varies in thickness from 1 to 2 cm. Walking stick is about 90 cm long. To the right, the upper mafic layer clearly cuts downward across the underlying chill (3) and felsic material (2) below that. (Photos: R.A. Wiebe)

Figure 5. Field photos of the chilled basal contacts of mafic sheets. **(a)** Mafic layer rests on hybrid rocks with weak gradation upward to more felsic material (Pleasant Bay intrusion). **(b)** Strongly lobate, convex downward base of mafic layer with no apparent upward escape of trapped liquid in felsic cumulate (Pleasant Bay intrusion) **(c)** Mafic layer rests on more leucoratic hybrid rocks with highly lobate convex downward base and prominent accumulation of residual liquid at crests between lobes. Later solidification of mafic layer led to fracturing and upward escape of

trapped felsic magma at the crests (Pleasant Bay intrusion). **(d)** Highly lobate base of ~50 m thick mafic layer. The amplitude of the mafic lobes are 5 to 10 m and the wavelength is ~25 m (Vinalhaven intrusion) (see Bain et al. 2013). (Photos: R.A. Wiebe)

Figure 6. Silicic pipes fed by underlying felsic cumulates beneath the base of mafic replenishments. **(a)** 3-D view of pipes (Vinalhaven intrusion) **(b)** Vertical outcrop displays a section ~ parallel to the pipe axes (Vinalhaven intrusion). **(c)** Horizontal surface ~ perpendicular to pipe axes. These pipes vary upward in composition from granite near the base to pegmatite and open vugs at higher levels (Pleasant Bay intrusion). (Photos: R.A. Wiebe)

Figure 7. A thin chilled basaltic layer terminates to the right and presumably flowed in that direction. Felsic pipes that penetrated the chilled base of the layer and rose upward, curving to the right, reflecting continued flow after the pipe initiated. By the time the pipes approached the upper margin of the mafic flow, a chilled margin had been established, which trapped the upwelling felsic material (Cadillac Mountain intrusive complex). (Photo: R.A. Wiebe)

Figure 8. Thin mafic layers chilled on base and top that were sequentially emplaced onto hybrid cumulate material as the chamber floor was aggrading (Pleasant Bay intrusion). (Photo: R.A. Wiebe)

Figure 9. Gradational compositional variation in macrorhythmic layers. **(a)** Top to the left. Gradation from gabbro upward to felsic cumulate within about 1 m. Overlying basally chilled gabbro layer cut by diapiric felsic material fed from the top of the gradational layer (Cadillac Mountain intrusive complex). **(b)** Comparable relations in

the Pleasant Bay intrusion. Here a chilled mafic lens within the gradational layer caused interstitial melt within the hybrid cumulate to be trapped and collect along its lower margin. (Photos: R.A. Wiebe)

Figure 10. Strongly metamorphosed and deformed MASLI, Mount Hay, central Australia (Collins and Sawyer 1996, Bonnay et al. 2000). Top is to the right, and the layers are overturned. Hammer rests on the felsic upper part of a macrorhythmic layer, which is basaltic at the left margin of the photo. Note large feldspar crystals, which are equant on the subhorizontal surface, but highly stretched on the subvertical surface. The base of overlying basaltic layer consists of lobate lenses within granitic septa; the foot at the right edge of the photo rests on overlying homogeneous meta-basalt. (Photo: R.A. Wiebe)

Table 1. List of plutons with evidence for emplacement of mafic magma into a floored, more silicic magma chamber - with references.

Arc settings.

Halfmoon Pluton, Stewart Island, New Zealand (Mesozoic) (Cook 1988, Wiebe and Collins 1998, Turnbull et al. 2010).

Tuross Head pluton, Australia (Silurian) (Wiebe and Collins 1998).

Composite diorite intrusions of the Julianehab District, south Greenland (Proterozoic) (Windley 1965).[2]

Terra Nova Intrusive Complex, Antarctica (Paleozoic) (Perugini et al. 2005).

Tanoura Igneous Complex, SW Japan (Cretaceous) (Ishihara et al. 2003).[1]

Tottabetsu Plutonic Complex, Hokkaido, Japan (Tertiary) (Kamiyama et al. 2007).

Daiqianshan complex, Fujien, SE China (late Mesozoic) (Xu et al. 1999).

Negash Pluton, northern Ethiopia (late Proterozoic) (Asrat et al. 2004).

Tichka plutonic complex, Morocco (Paleozoic) (Fernandez and Gasquet 1994).

Cordillera del Paine pluton, southern Chile (Tertiary) (Michael 1991, (Leuthold et al. 2014).[2]

Gabbro-granite complex of Porto, western Corsica (Paleozoic) (Renna et al. 2006).

Piolard Diorite and Saint-Julien-la Vetre Monzogranite, France (Paleozoic) (Barbarin 1988).

Gil-Marquez Complex, south-west Spain (Paleozoic) (Castro et al. 1995).[1]

Layered amphibolite sequence, NE Sardinia, Italy (Paleozoic) (Franceschelli et al. 2005).

The Val Freda Complex, Adamello Massif, Italy (Tertiary) (Blundy and Sparks 1992).[2]

Sazava intrusion, Czech Republic (Paleozoic) (Janousek et al. 2004).

Gesiniec intrusion, Poland (Paleozoic) (Pietranik and Koepke 2009).

Northern Igneous Complex of Guernsey, Channel Islands (Cadomian) (Topley et al. 1990).[1]

The Elizabeth Castle Igneous Complex, Jersey, Channel Island (Cadomian) (Shortland et al. 1996).[1]

Ingonish pluton, Cape Breton Island, Nova Scotia, Canada (Cadomian) (Wiebe 1974a, b).

Burnett Inlet Plutonic Complex, Alaska (Tertiary) (Lindline et al. 2004).

Rattlesnake Mountain Pluton, southern California (Mesozoic) (MacColl 1964).[1]

Diorite of the Rockslides in El Capitan granite, Sierra Nevada, California (Ratajeski et al. 2001).[1]

Aberdeen complex in granite of Goodale Mtn. (Mesozoic) Sierra Nevada, California (Mesozoic) (Coleman et al. 1995).[2]

Hornblende gabbro sill complex at Onion Valley, Sierra Nevada, California (Mesozoic) (Sisson et al. 1996).[2]

Guadalupe Igneous Complex, Sierra Nevada, California (Mesozoic) (Putirka et al. 2014).

Pyramid Peak pluton, Sierra Nevada, California (Jurassic) (Wiebe et al. 2002).

Diamond Creek pluton, Grand Canyon, Arizona (1736 Ma) (David Hawkins - personal communication 2015).

Ruby pluton, Grand Canyon, Arizona (1716 Ma) (David Hawkins - personal communication 2015).

Extensional environments.

Austurhorn, SE Iceland (Tertiary) (Blake 1966, Mattson et al. 1986, Furman et al. 1992a,b, Weidendorfer et al. 2014).[1]

Kialineq centre, East Greenland (Tertiary) (Brown and Becker 1986, Lesher - personal communication 2015).

Lamboo Complex, east Kimberley, Western Australia (~ 1800 Ma) (Blake and Hoatson 1993).

Mafic-felsic rocks of Mount Hay, central Australia (~ 1800 Ma) (Bonney et al. 2000).[1]

Vradal pluton, central Telemark, southern Norway (late Proterozoic) (Sylvester 1998).

Saint Jean du Doigt bimodal intrusion, France (late Paleozoic) (Barboni et al. 2008, Caroff et al. 2011).[1]

Barth Island intrusion, Nain, Labrador (~ 1300 Ma) (deWaard 1976).[1]

Newark Island Layered Intrusion, Nain, Labrador (~ 1300 Ma) (Wiebe 1988).

Tigalak layered intrusion, Nain, Labrador (~ 1300 Ma) (Wiebe and Wild 1983).

Fogo Island intrusion, Newfoundland, Canada (422 Ma) (Currie 2003, Andrew Kerr – personal communication 2009).

Virginia Dale intrusion, Colorado and Wyoming (Proterozoic) (Vasek and Kolker 1999).[1]

The Maloin Ranch pluton, Laramie, Wyoming (Proterozoic) (Kolker and Lindsley 1989).[1]

Isle au Haut Igneous Complex, Maine (Silurian) (Chapman and Rhodes 1992).

Pleasant Bay intrusion, coastal Maine (~420 Ma) (Wiebe 1993).

Cadillac Mountain intrusive complex, coastal Maine (~420 Ma) (Wiebe 1994).

The Spruce Head composite pluton, Maine (Silurian) (Ayuso and Arth 1997).[1]

Moosehorn plutonic suite, Maine and New Brunswick (Silurian) (Hill and Abbott 1989).[1]

Vinalhaven intrusive complex, coastal Maine (420 Ma) (Wiebe and Hawkins 2015).

Florida Mountains granite, southwest New Mexico (510 Ma) (McMillan and McLemore 2004, D.P. Hawkins - personal communication 2015).

Little Hatchet pluton, southwest New Mexico (1077 Ma) (McMillan and McLemore 2004, D.P. Hawkins - personal communication 2015).

Aztec Wash Pluton, Northern Colorado extensional zone, Nevada (Tertiary) (Patrick and Miller 1997, Harper et al. 2004).[1]

Searchlight Pluton, Northern Colorado extensional zone, Nevada (Tertiary) (Bachl et al. 2001).[1]

[1] Intrusions included based in part on the author's visit to the occurrence.

[2] Intrusions included based on field relations described in the reference, even if the reference cited does not interpret the pluton in this way.

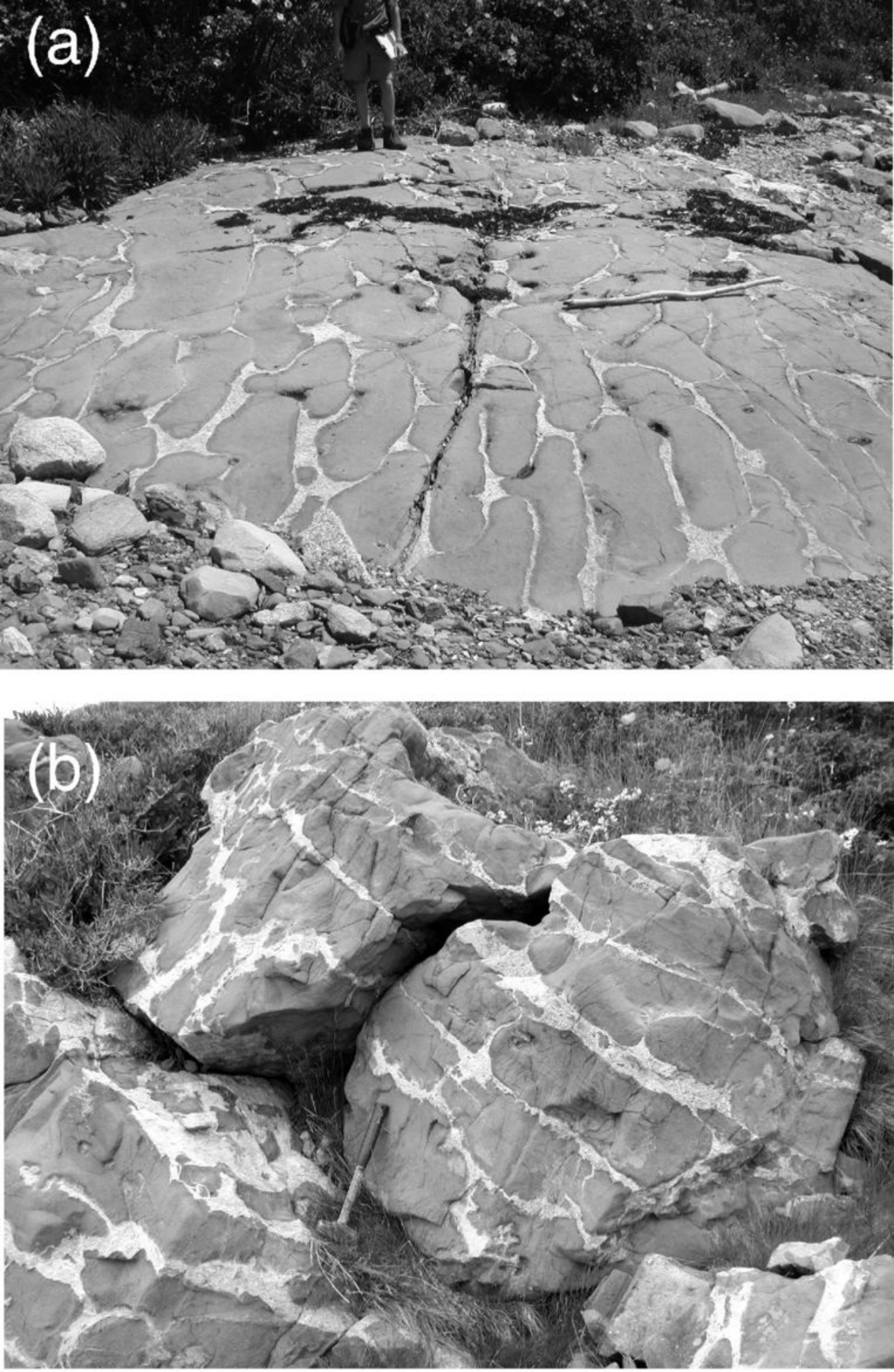

Figure 1

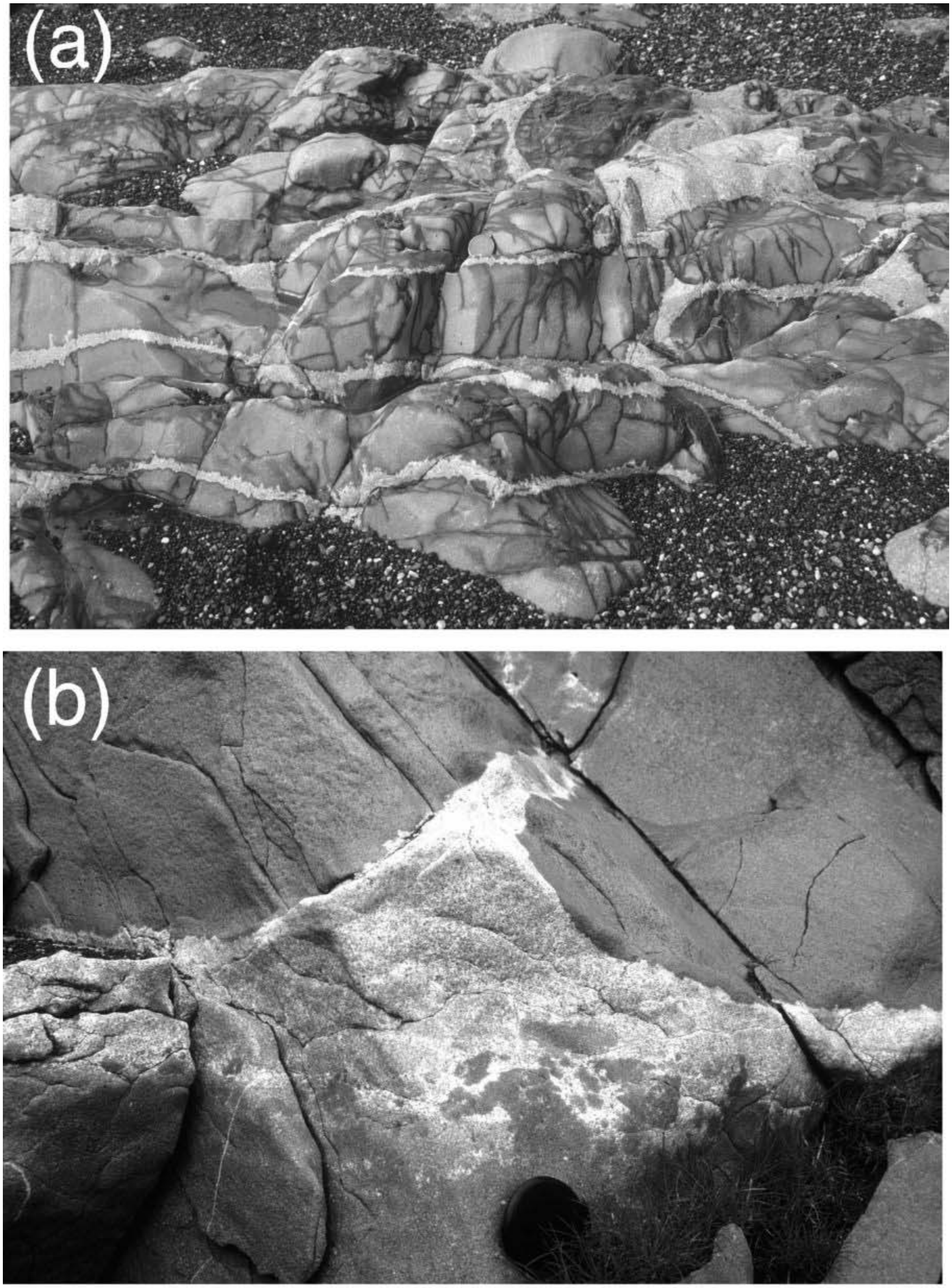

Figure 2

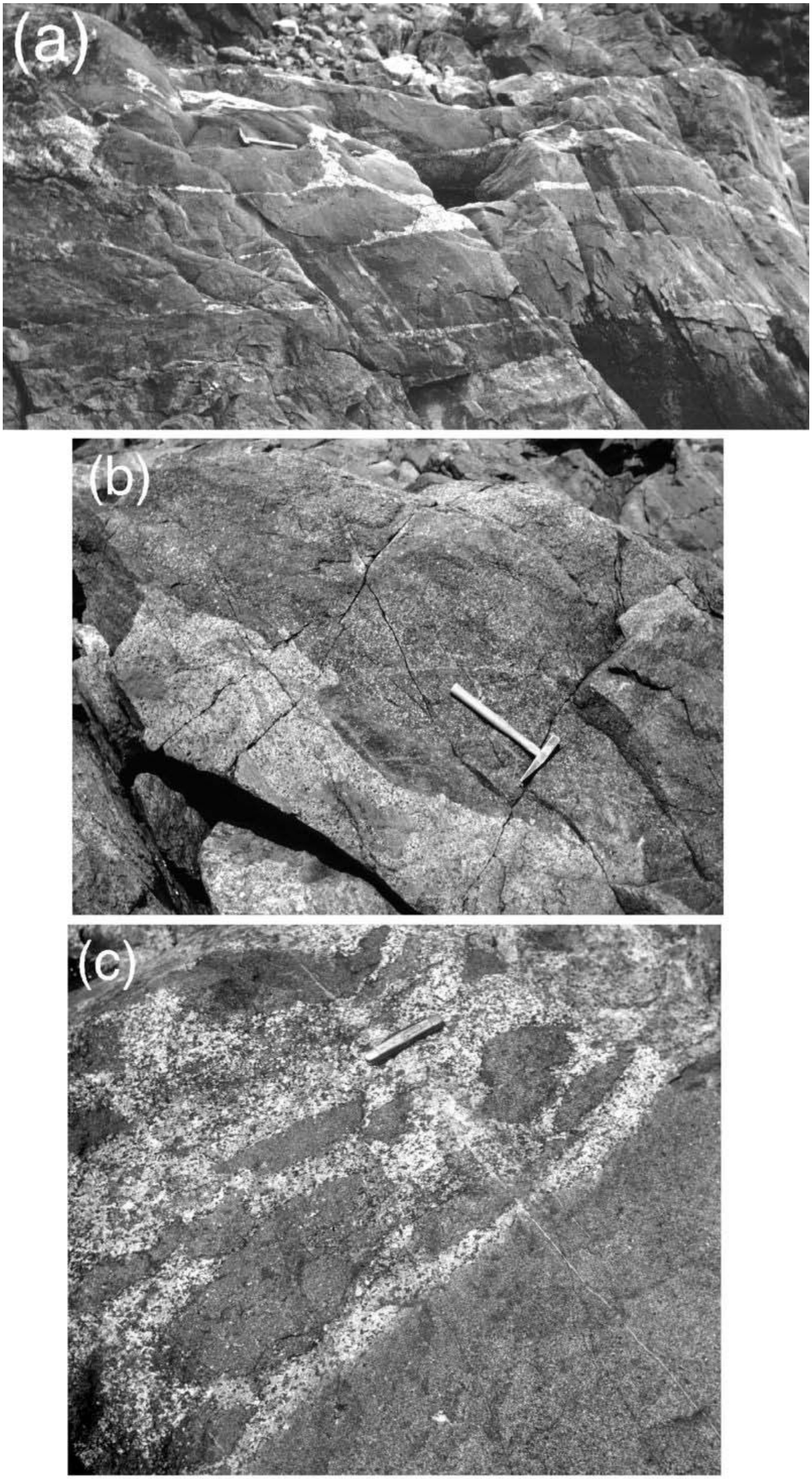

Figure 3

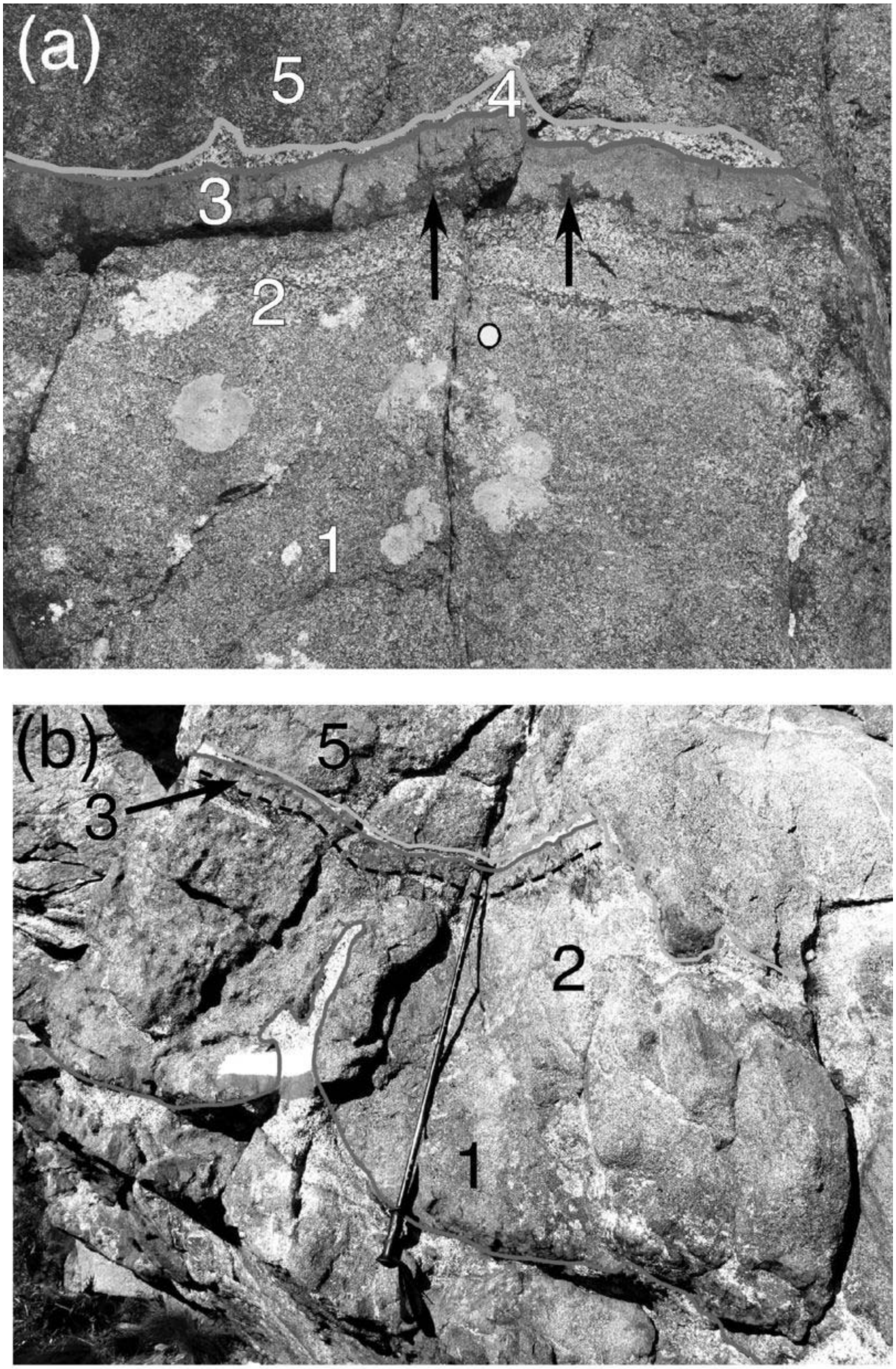

Figure 4

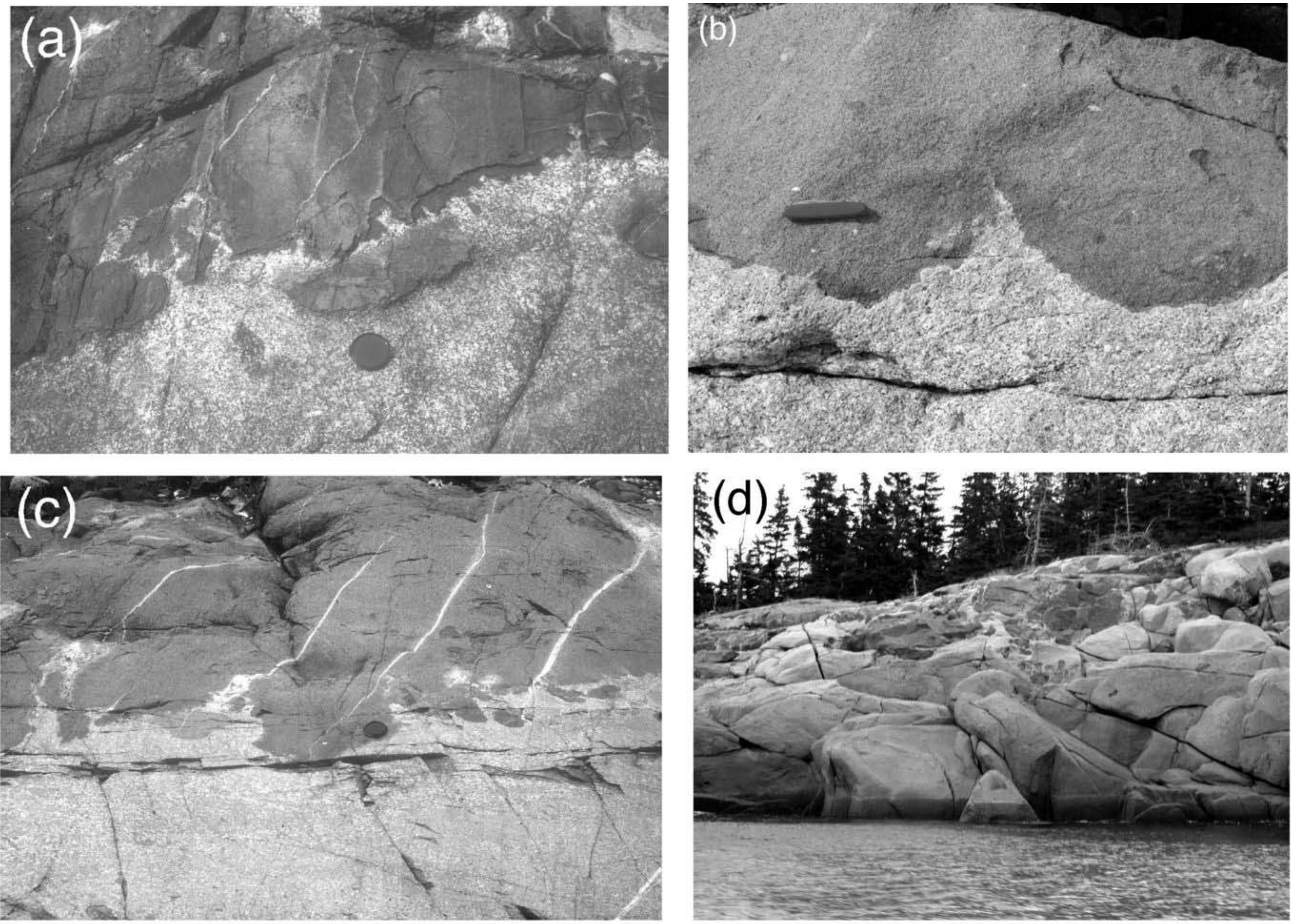

Figure 5

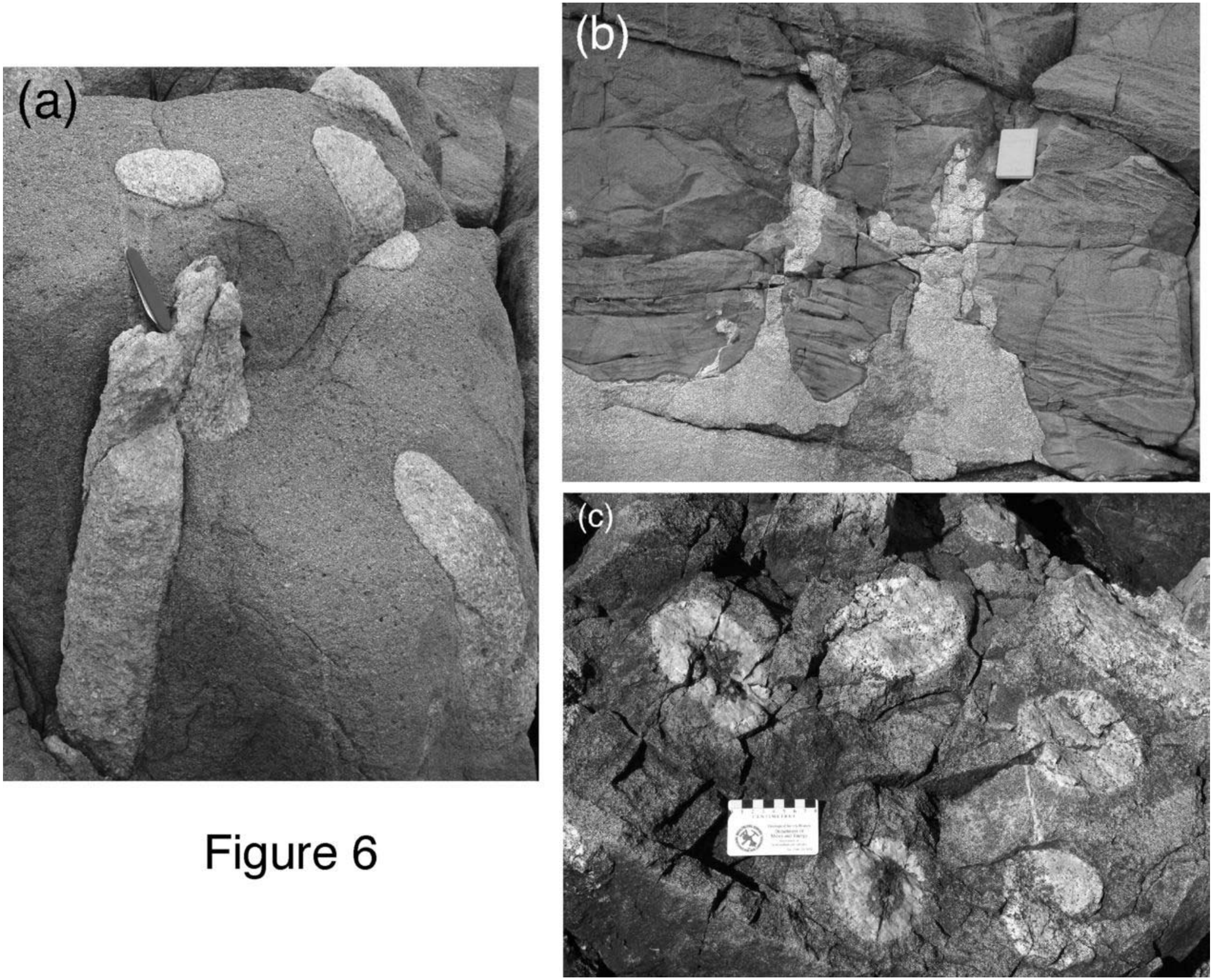

Figure 6

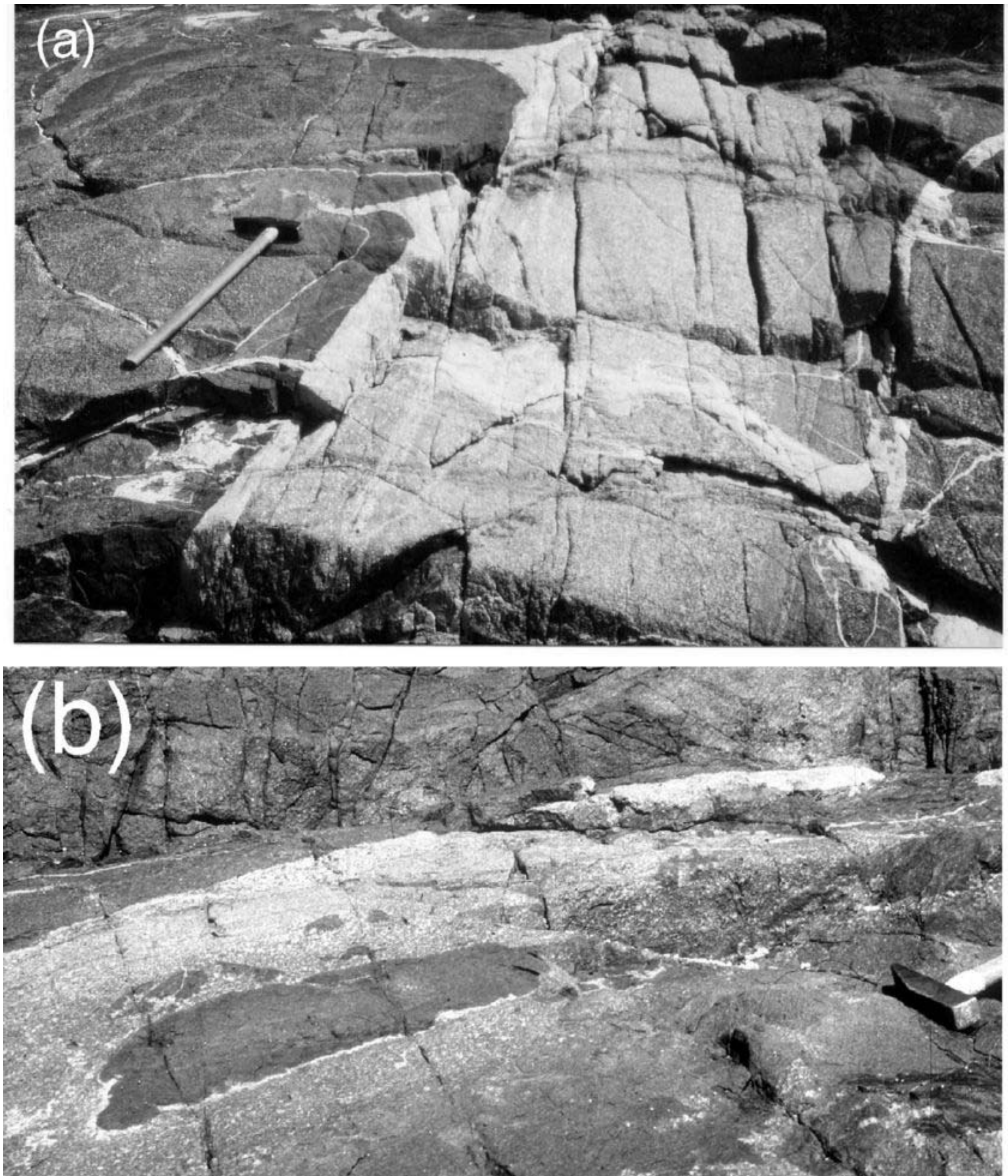

Figure 9