Evidence of small-volume igneous diapirism in the shallow crust of the Colorado Plateau, San Rafael Desert, Utah

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ABSTRACT

Magma is transported through Earth's solid crust by two different processes, diking and diapirism, although other mechanisms, such as porous and channeled flow, can transport melt through partially molten crustal areas. Dikes are ubiquitous indicators of the transport of magma in the shallow crust by brittle fracture, and there is ample geological and geophysical evidence supporting diking as a magma-ascent mechanism through the crust. On the other hand, igneous diapirism, involving magma ascent by gravitational instability and requiring viscous or plastic flow of country rock ("hot Stokes" diapirs), is often invoked as a magma-transport mechanism restricted to the ductile upper mantle or lower crust. However, unequivocal geological field evidence for igneous diapirism has proven elusive and has been a matter of considerable debate. We report geological and geophysical evidence showing that Pliocene sills emplaced in the upper levels of brittle continental crust of the Colorado Plateau in the San Rafael subvolcanic field (Utah) became gravitationally unstable by mechanically altering the overlying sedimentary rocks. These sills grew into structures that we recognize as domes and plugs at the current level of exposure. Some of these plugs continued to transport magma to shallower levels of the continental crust and eventually acted as conduits feeding volcanic eruptions. Our geological and geophysical findings indicate that gravitational instability is a viable mechanism for the initiation of magma ascent in the upper continental crust for small volumes of basaltic magma under specific conditions.

INTRODUCTION

The initiation of magma ascent as gravitational or Rayleigh-Taylor instabilities from a source region, and subsequent transport through the lithosphere, has been explored through several experimental studies (Ramberg, 1970; Marsh and Carmichael, 1974; Marsh, 1979; Kerr and Lister, 1988; de Bremond d’Ars and Jaupart, 1995). The mechanics of igneous diapirism, particularly within the context of granitic magmas, has also been studied from theoretical perspectives (Marsh, 1982; Schmeling et al., 1988; Rubin, 1993; Podladchikov et al., 1993; Weinberg and Podladchikov, 1994; Burov et al., 2003). In the field, magmatic diapirs and their mode of emplacement are usually inferred from large igneous intrusive bodies or plutons and their contacts with host country rocks (e.g., Bateman, 2002; Paterson and Fowler, 1993; Paterson and Farris, 2006; He et al., 2009). Due to the large vertical dimension of these intrusive bodies, only a fraction of their structure is usually exposed, and therefore the link with their magmatic source remains largely undetected. Thus, the mechanisms that govern their origin and ascent are currently widely debated (Petford, 1996; Weinberg, 1996; Miller and Paterson, 1999; Petford and Clemens, 2000).

Substantial erosion associated with the uplift of the Colorado Plateau has exposed low-volume basaltic intrusions, such as dikes, plugs, and domes, in a small area (200 × 100 m), which we refer to as the Carmel outcrop, in the San Rafael Desert, Utah. This locality (Figs. 1A and 1B) provides a unique opportunity to explore the mechanisms that govern the initiation of magma ascent from sill-like intrusions in the shallow continental crust. Here, we report geological and geophysical observations that show that the small mafic intrusions, generally <10 m in diameter, that constitute the Carmel outcrop are linked to underlying feeder sills, from which these plugs and domes ascended. Remarkably, plugs and domes in this outcrop are not physically connected to dikes at the stratigraphic level of the outcrop, and they did not form by widening or erosion of a dike. Rather, map data are consistent with emplacement of domes and plugs by gravitational instability. Thus, in contrast to larger plutons, where the connection with the magmatic source is mostly inaccessible, in this outcrop, we can infer details of magma ascent directly from geological and geophysical observations. Some of these details are surprising, but they also are physically consistent with models proposed for magma ascent on much larger scales (e.g., Marsh, 1982; Weinberg and Podladchikov, 1994).

Geologic mapping of domes and plugs, together with deformation of the host sedimentary section, provides fundamental evidence of ascent of these small magmatic bodies by diapirism. Geologic mapping also provides important clues about the sequence of events during magma emplacement in the area, and evidence for the eruption of this magma at the surface. High-resolution geophysical surveys support these observations by providing a three-dimensional (3-D) perspective of the shallow subsurface structure of the Carmel outcrop. These surveys include mapping magnetic anomalies, which outline the planimetric area of shallow sills from which the domes and plugs rose; ground-penetrating radar (GPR), which reveals the underground undulating structure of the upper contacts of the sills to be consistent with the plugs and domes mapped at the ground surface; and electrical resistivity data that support the interpretation of the depth to the sill and geometry of shallow domes and plugs. Together, these data indicate that small-scale magmatic diapirism occurred in the shallow sedimentary section and transported magma to shallower crustal levels and even to the surface, feeding volcanic eruptions.
The Carmel outcrop (Fig. 1B) is part of a subvolcanic field consisting of Pliocene (ca. 4 Ma) basaltic intrusions, such as dikes, sills, and plugs, that intrude in Middle Jurassic nearshore clastic rocks of the San Rafael Group (Delaney and Gartner, 1997) (Fig. 1A). The Carmel outcrop consists of several basaltic plugs and domes distributed on both sides of a N-S–trending dike (Fig. 1B). By plug, we refer to a structure consisting of an inner igneous or volcaniclastic lithofacies that is surrounded by wall rock with vertical or steep inward-dipping contacts. The term dome is applied to structures where the contacts and wall rocks are dipping outward, with nearly constant dips, with respect to the inner igneous lithofacies. Wall rocks are exposed around the plugs and domes and at the contacts of several plugs. The wall rocks consist of regionally horizontal beds of fine-grained limestone, siltstones, and shales interbedded with gypsum layers of the banded and gypsiferous members of the Carmel formation. The overburden thickness at the time of intrusion in the Pliocene (ca. 4 Ma) is estimated at ~800 m based on palaeotopographical reconstructions (Pederson et al., 2002).

It has been suggested that some enlarged features along the dike, such as buds (Wentworth and Jones, 1940; Delaney and Pollard, 1981), may represent localization of the flow of magma along the dike. However, as the geological map (Fig. 1B) of the Carmel outcrop shows, some domes and plugs are offset from the dike and reached the level of current exposure independent of the dike. This feature of the Carmel outcrop is not consistent with classic models of fissure eruptions, which rely on localization of flow to form conduits along dikes (e.g., Wylie et al., 1999). Rather, magmatic structures are isolated from the dike at the same stratigraphic level, implying a different mechanism of ascent in these plugs and domes.

We focused on sectors of the Carmel outcrop where the exposures contain geological information most pertinent to understanding the mechanism of ascent. One plug occurs in...
the central portion of the outcrop (Fig. 2; note that Figs. 2–4 show enlarged areas of Fig. 1B), together with a series of domes and basanite outcrops, west of the N–S–trending dike. This plug is roughly circular in plan section and consists of basanite free of wall-rock xenoliths (see Table 1 sample CSCB) with vesicle content from 5% to 7% and diabase texture very similar to the dike rock (see Table 1 sample CDK-4).

The density of the basanite was measured in the laboratory by weighing a hand sample and measuring its volume. Viscosity was estimated from two thin sections and accounted for in the density calculation. The estimated density values are 2143 and 2198 kg m⁻³. The wall rock consists of banded, silica- and carbonate-rich siltstones with thin interbedded shaly beds (see Table 1 sample SS). The dip of the wall-rock layers varies along the contact; there are nearly flat outward- and inward-dipping beds along the east and north contacts, respectively, and overturned beds at the south contact.

Two domes crop out a few meters south of the described plug. These domes are stratigraphically lower than the ground-surface expression of the plug, and they are surrounded by outward-dipping (40°) fine-grained thinly layered limestone (see Table 1 sample CAR-1). The southernmost dome is very small and has an inner basaltic core of ~50 cm. Its outward-dipping wall rock (~40°) is clearly visible in field exposures; however, it is not drawn on the map of Figure 2 due to its small size. Note also that this limestone is exposed nearby and dips inward in the area surrounding the plug.

A number of irregular basanite outcrops are exposed through a dry creek bed ~5 m west of the northermost dome (Fig. 2). These outcrops reveal the presence of an intrusion off the dike and beneath the plug and domes of this sector. As described in the following paragraphs, these outcrops are interpreted to be a sill located in the shallow subsurface beneath the domes and plugs mapped at higher stratigraphic levels.

A second plug is exposed to the south and ~6 m west of the dike (Fig. 3A). This plug is roughly circular in plan view, with a diameter of 16 m, and it shows a more complex structure than the plug in the central sector. This plug consists of a peperitic rock (see Table 1 sample CAR-3) with isolated domains of fine-grained sandstone, showing flow textures and dispersed juvenile basanite enclaves within a fine-grained matrix consisting mainly of clinopyroxene microlites and quartz. We interpret these lithofacies as the result of thorough mingling between unconsolidated fine-grained sandstone and a basanitic magma. Vertically elongated vesicles are abundant, suggesting the boiling of the wet peperitic deposit, and also indicating vertical movement of the magma within the conduit. A slightly off-center, circular in plan section, small basanite outcrop is exposed within the peperitic lithofacies. This basanite (see Table 1 sample CBC-core) is free of xenoliths and comparatively denser than the basanite in the northern sector, likely representing a late pulse of degassed magma along the conduit. The contact of this plug is complex; overturned wall-rock layers (indicated schematically on the west side of the plug in Fig. 3A) of the banded siltstone described in the previous plug contact (see Table 1 sample SS) alternate with thin (~1 m) lenses of basanite (Fig. 3B). The contact between the basanite and the wall rocks is in general very irregular, possibly indicating that the yield strength of the sedimentary wall rock was dramatically reduced, allowing viscous flow. Note that in some areas the preexisting structure of the wall rock is preserved, while in other domains, the original sedimentary banding is completely obliterated (Fig. 3C). This idea of wall-rock viscous behavior is also supported by field evidence of local folding (Fig. 3D). Note that the exposures of stratigraphically lower limestone wall rocks crop out ~25 m northwest of the plug and dip southeast toward the plug (Fig. 3A), as in the previous sector.

Another plug is exposed in the southernmost sector of the Carmel outcrop (Fig. 4A). Among all of the mapped structures, this plug is the largest and most complex in terms of interior lithofacies and geometry. The overall geometry is bilobate—an irregular southern lobe is connected to a more circular northern lobe that intersects the N–S-trending dike. The dominant lithofacies in the north lobe consist of volcaniclastic rock with fine-grained sandstone xenoliths incorporated in an aphyric basanite matrix, and locally peperitic domains. Glassy droplets within the matrix (Fig. 4B) reveal a pyroclastic origin of this lithofacies, and the presence of abundant armored lapilli (Fig. 4C) indicates that this volcaniclastic rock was produced during volcanic eruptions (Macías et al., 1997).

The southern lobe mainly consists of dense basanite that is free of xenoliths, similar to the basanite described in the previous plug (Fig. 3),
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also indicating a late intrusive pulse of degassed magma. This lithofacies is also exposed through a roughly circular domain within the volcaniclastic lithofacies in the northern lobe. A body of globular to blocky peperite-like rock between the two lobes (Fig. 4A) reveals the mingling of magma with sedimentary rocks at some point in the history of this volcanic conduit. In the west rim of the plug, an inward-dipping contact is exposed (Fig. 4A). The bedding in the wall rock is nearly subhorizontal, which suggests that the upward diverging contact in this part of the plug was created by mechanical erosion by the flowing magma through the conduit. Locally, sandstone xenoliths and elongated vesicles in the basanite are vertically oriented, subparallel to the eroded contact, suggesting vertical mafic flow near the conduit walls. Note also that a few meters east of this plug, wall-rock strata dip northwest, toward the plug, again consistent with deformation of the sedimentary section during emplacement of the domes and plugs.

GEOPHYSICAL DATA

A series of geophysical surveys (magnetics, ground-penetrating radar [GPR], and resistivity) was carried out at the Carmel outcrop to explore the subsurface geometry of the major features of the outcrop (Figs. 5 and 6). Specific goals of the geophysical surveys were to: (1) determine if the basanite outcrops found west of the domes and plugs of the Carmel outcrop were part of a sill that extends beneath the entire structure; (2) determine the lateral extent of this sill; (3) image the profile of domes that crop out on the Carmel outcrop with depth; and (4) identify similar domes in the subsurface that do not crop out.

Magnetic Anomalies

In this area, magnetic anomalies are caused by the contrast between basanite, which has relatively high magnetic susceptibility and remanent magnetization, and the surrounding sedimentary section, which has comparatively very low susceptibility and remanent magnetization. Because of this large contrast in magnetic properties of the igneous and sedimentary rocks, magnetic anomalies can reveal the lateral extent of basanite rocks in the subsurface associated with sills. Magnetic data were collected with a Geometrics 858 magnetometer interfaced to a differential global positioning system (GPS) for positioning. In total, ~24,000 measurements were collected across the map area, and maximum spacing between measurements was <5 m. The International
Geomagnetic Reference Field was subtracted from the magnetic data, and anomalies were contoured and compared with the locations of basanite plugs, domes, and dikes (Fig. 5). Magnetic data were also collected over a wider area at lower resolution in order to verify that magnetic anomalies did not persist beyond the mapped area shown in Figure 5.

Relatively large-amplitude (>500 nT) magnetic anomalies occur in the area of the Carmel outcrop. These magnetic anomalies persist over a much greater area than individual outcrops and include two well-defined anomalies in the map area that are defined by elongate positive magnetic values bordered on the north and east by negative magnetic values. Both of these anomalies are consistent with shallowly buried, normally magnetized basanite. In addition, very short-wavelength anomalies occur associated with individual structures, such as N-S–trending dike segments and individual domes and plugs.

Several features of the magnetic map indicate that comparatively long-wavelength magnetic anomalies are best explained by the occurrence of sills. First, the magnetic anomalies are quite wide compared to individual outcrops at the surface. The positive magnetic values, for example, in the southern portion of the magnetic map (Fig. 5) encompass a zone roughly 50 m in width and >100 m in length, far larger than individual outcrops. Short-wavelength magnetic anomalies associated with the N-S–trending dike segments, in contrast, are on the order of <5 m in width. Second, the magnetic anomalies extend to the basanite exposures at a dry creek west of the southernmost dome of the central sector (Fig. 1A), which are interpreted to be outcrops of an underlying sill. Third, the overall shape of the magnetic anomalies is consistent with a thin horizontal magnetized sheet, although undulating magnetic anomalies at shorter wavelengths also indicate undulations in the depth to the top of the sill, consistent with the presence of domes and dome-like structures.

The sill south of the UTM coordinate 4272850 N (Fig. 5) is ~50 m wide on average and extends to both sides of the N-S–trending dike. The magnetic data indicate that this sill terminates on its north side where the N-S–trending dike is segmented and steps left. Magnetic anomalies persist north of this left step, but they have longer wavelengths than those to the south. These longer wavelength anomalies suggest that a second sill is present at slightly greater depth than the sill located to the south. Both sills are best outlined in map view where magnetic gradients are highest, as indicated by the dashed red line in Figure 5.

Ground-Penetrating Radar

GPR profiles (G-G’ on Fig. 6A, G1-G1’ on Fig. 6B, and G2-G2’ on Fig. 6C) were acquired with Sensors and Software Inc. PulseEKKO 100 system with 100 MHz antennas and 400 V transmitter. Data acquisition parameters were: 1 m transmitter-receiver separation, 16 traces stacked at each acquisition point, ~0.05 cm between traces, and a sampling interval of 0.8 ns. The raw data traces were dewowed, time-zero corrected, resampled to 5 cm spacing, and gained with an automatic gain control (AGC) filter (14 ns window). On line G–G’, traces were corrected to zero offset, with an average background subtracted to emphasize dipping units and remove system noise, and migrated with a constant velocity diffraction stack migration. The best-fitting velocity for the interval above the first bright reflector, 0.09 m/ns, was derived from a nearby common midpoint profile and used to migrate the data and plot the depth axis. Data processing was done with a combination of algorithms from Sensors and Software’s pulseEKKO 4.2 software, original Matlab algorithms, and ReflexW from Sandmeier Scientific Software.

A high-amplitude continuous undulating GPR reflector at 20–50 ns two-way traveltime (red line, Fig. 6A) showa symmetrically around the point where the largest dome outcrops (Figs. 1B and 2). This reflector parallels the attitudes of the basanite–wall-rock contact in the overlying exposure, so we interpret the source of the bright GPR reflector as a lithologic or porosity variation associated with this contact. Note that another dome is revealed ~6 m north of this dome, where the basanite–wall-rock interface lies underground. Two other GPR profiles (Figs. 6B and 6C) across the northernmost magnetic anomaly in Figure 5 clearly reveal the underground geometry of the upper sill contact and indicate that this contact is deflected downward in the area surrounding the northernmost mapped plug (see Fig. 1B). This is consistent with structural data measured in the surrounding wall rocks.

Resistivity

Resistivity data along two profiles, W-W’ (Fig. 6D) and N-N’ (Fig. 6E), were collected with a Campus resistivity system with 47 electrodes and a Wenner geometry. Electrode
spacing was 1 m on profile W–W′ and 1.5 m on N-N′. The data were inverted with default inversion settings using Res2dinv from Geotomo, Inc. The inversion results shown here have root mean square (rms) errors of 4% and 7%, respectively, for profiles W–W′ and N–N′. These profiles reveal resistivity anomalies beneath the plug and domes of the central sector. Although the W–W′ profile shows a roughly inverted drop-like structure beneath the plug, because the survey is two-dimensional, these data cannot resolve the detailed strongly three-dimensional geometry of this structure. Instead, the shape of this resistivity anomaly could be equally generated by a cylindrical or an inverted drop-like, three-dimensional body (either consistent with a diapiric shape to the body). The N–N′ resistivity profile delineates a subhorizontal resistivity anomaly, which suggests the presence of a sill of about ~4 m of average thickness beneath the plugs and domes of the central sector of the Carmel outcrop.

**MAGMA ASCENT INITIATION**

Remarkable exposures of the Carmel site provide access to the roots of magmatic conduits at the upper contacts of small-volume sills in the shallow (<1 km) crust. Geological and geophysical observations indicate that magma ascended from these sills at both sides of the N-S–trending dike, forming plugs and domes. These observations provide clues to infer the mechanism that governed the initiation of magma ascent from the sills to shallower crustal levels.

Before discussing a plausible mechanism for magma ascent, it is important to point out that the structure of the upper contact of the sill imposes constraints on the rheology of the wall rocks at the time of magma ascent initiation. The presence of small isolated domes requires viscous or plastic deformation of the wall rocks after a dramatic reduction of yield strength. If the wall rocks behaved elastically, a laccolithic structure would have formed, producing the concave-upward deflection of the whole contact (e.g., Jackson and Pollard, 1990) rather than localizing the deformation through domes smaller than a few meters in diameter (see domes in Fig. 2). An alternative explanation for the domes involves accommodating the deformation of the dome-like structures by brittle fracturing or displacement through preexisting fractures; however, no evidence of faulting is found in the wall rocks of the mapped domes. A key question then is how this reduction in yield strength occurred. In principle, a thermal activated process could be invoked. However, taking into account the relatively short time scales involved during such small-volume magmatic activity, we consider it unlikely that a significant extent of wall rock was heated to the high temperature required to dramatically reduce the wall-rock yield strength. In fact, negligible thermal effects have been observed in the outcrop at plug and dome contacts. An alternative mechanical process has been suggested in which heat from the basaltic intrusion into cold wet wall rock causes pore fluid expansion (McBirney, 1959; Delaney, 1982), leading to either liquefaction or fluidization of the wall rocks in short time scales (Maltman and Bolton, 2003). During liquefaction, the sediment load is borne by pore fluid, cohesion is lost, yield strength is dramatically reduced or becomes negligible, and the mass of sediment behaves effectively as a viscous fluid. A good example of sediment liquefaction is found in the Northern Territory of Australia (Needham, 1978), where, as a consequence of loading by an active lava flow, underlying sediments became liquefied and ascended by gravitational instability, preserving their preexisting bedding structures. On the other hand, during fluidization, sediment strength is lost as grains become dragged by moving interstitial fluids (Maltman and Bolton, 2003). Fluidization then requires the influx of external fluids, and preexisting structures are usually obliterated. Sedimentary elastic wall rocks overlying the sills in the Carmel outcrop are porous rocks that in the Pliocene, at the time of intrusion, under shallow crustal conditions (~1 km deep), were likely wet and additionally saturated with fluids.
We interpret this as evidence of liquefaction.

Figure 3. In Figure 3C, note that the wall rock is folded, and the preexisting bedding is preserved.

Figure 6. Ground-penetrating radar (GPR) and resistivity profiles across the plugs and domes of the Carmel outcrop. See sketch for profile location. (A) Migrated GPR profile G–G’ across an outcropping dome (in red letters). The subsurface sill–wall rock contact is delineated by a red solid line. Note the presence of another buried dome ~6 m north of the mapped dome. (B–C) GPR profiles G1–G1’ and G2–G2’ across the northernmost magnetic anomaly (green dashed line). Note that in the northwest part of the profiles, the upper contact of the sill is deflected downward. (D) Resistivity profile W–W’ across the plug in the central area of the Carmel outcrop (in blue letters). Note the inverted drop-like shape of the anomaly mapped west of the dike. (E) Resistivity profile N–N’ through the east side of this plug and domes revealing an ~4-m-thick (average) resistivity anomaly that corresponds to an underlying sill.

Different lines of evidence shed light on the mechanism for the initiation of magma ascent in the Carmel outcrop: (1) viscous behavior of the wall rocks discussed in the previous section; (2) scattered and isolated source areas for magma ascent at the upper contact of the sills, such as plugs and domes, rather than a laccolithic structure; (3) inward-dipping stratigraphy surrounding all the plugs (Figs. 1, 2, 3, 4, 6B, and 6C) and overturned contacts (Figs. 2 and 3); and (4) a density contrast between the wall rocks and magma, with magma being less dense. The density of basanite in the plug in Figure 2A has been measured in two samples and is 2143 and 2198 kg m⁻³, with 5% and 7% of vesicularity, respectively. These values represent an upper bound, because when magma intruded the shallow sill, it was likely degassing and forming bubbles. Upon crystallization in subvolcanic conditions (the basanite has diabasic texture), a fraction of these bubbles collapsed and were not preserved as vesicles. Typical density values for sedimentary rocks such as sandstones, shales, siltstones, and limestones are 2400–2600 kg m⁻³, giving an approximate density contrast range of 200–400 kg m⁻³. These observations, when considered together, suggest a mechanism for the initiation of magma ascent by gravitational instability from the upper contact of the sill once the yield strength of the wall rocks had been dramatically reduced or lost by liquefaction and/or fluidization.
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Overpressure

An alternative mechanism governing the initiation of magma ascent might be overpressure within the sill. However, we find this scenario problematic because it necessitates an explanation for pressure becoming localized in such small areas (the smallest dome has a diameter of ~50 cm; see Fig. 2), which subsequently evolved into the plugs and domes we observe in the field. When pressurization is invoked as a mechanism driving deformation (Jackson and Pollard, 1990), it involves deformation about the entire intrusive body. We recognize that, in principle, it is possible for heterogeneities in the wall rocks to cause pressure localization above every incipient dome or plug. However, this would imply a few more additional assumptions. Another problematic aspect of the overpressure mechanism arises from our observations of the wall-rock structures. The geometry of the wall rocks is different depending on the forces governing the deformation of the upper contact of the sill (Fig. 7). When buoyancy forces dominate the ascent through gravitational instability, magma ascends, the surrounding wall rocks sink into the sill by downward flow, forming a rim syncline (Fig. 7A). That is, vertical or overturned contacts and inward-dipping stratigraphy (toward the center of the plug) are created. In contrast, when overpressure due to new incoming magma in the sill causes deflection of the upper contact, a dome or laccolithic structure with no inward-dipping stratigraphy can be accommodated (Fig. 7B). Inward-dipping stratigraphy cannot be created unless a net volume loss of magma occurs, for example, during volcanic eruption. In the Carmel outcrop, there is only one plug, the southernmost plug, with unequivocal evidence of volcanic eruption, although inward-dipping stratigraphy is characteristic for all the plugs mapped (see Figs. 1, 2, 3, 4, 6B, and 6C). Even assuming that all the other plugs represent conduits of erupting vents at the surface, the overturned contacts on Figures 2 and 3 would still remain unexplained by an overpressure mechanism. Thus, we assert that the mechanism for the initiation of magma ascent from the sills by gravitational instability rather than overpressure is better supported by observations.

CONCLUSIONS

Geological and geophysical data indicate that small plugs and domes mapped at the Carmel outcrop rose from horizontal sills. Different lines of evidence, such as: (1) viscous deformation of the wall rocks, (2) scattered and isolated sources of magma, ascent through plugs and domes, (3) density contrast between wall rocks and lower-density magma and (4) inward-dipping stratigraphy and overturned contacts, point to a mechanism for the initiation of magma ascent from the sills governed by gravitational instability.

We envision the following geological scenario to explain the Carmel outcrop (Fig. 8): A
N-S dike feeds a silt into wet sedimentary wall rocks in the shallow continental crust of the Colorado Plateau. Heat flow from the intrusion into the cold wall rocks causes pore-fluid expansion at the contact, leading to liquefaction and consequently to a great reduction of the strength of the sedimentary rocks but preserving preexisting sedimentary structures. The wall rocks can therefore effectively deform as a viscous fluid, and, because the density of magma is lower than that of the overlying wall rocks, gravitational instability is triggered (Fig. 8A). Magma ascent is initiated, but since magma influx along the feeder dike is not homogeneous, some areas are arrested and preserved as small domes, while other areas continue to grow (Fig. 8B). As the influx of magma is steady through these areas, degassing of the intrusion feeds an influx of volatiles into the porous wall rocks that leads to fluidization, obliterating preexisting sedimentary structures. In some of these areas, magma continues its ascent toward the surface, where it mixes with unconsolidated sediments, as suggested by globular and blocky peperite described in the plug in Figure 4, and eventually feeds a volcanic eruption (Fig. 8C). As the eruption wanes, rock blocks from the vent infill the conduit, mixing with the last pulses of degassed magma and forming the peperitic rocks that we observe in some of the plugs (Fig. 8D).

In the light of these observations, gravitational instability is a viable mechanism for the initiation of magma ascent from a low-volume magmatic reservoir in the shallow crust. Gravitational instability is likely to happen in areas where feeder dikes intersect or form sills, where a continuous influx of magma and volatiles is provided, and where wall rocks are wet and porous, a common situation in the shallow continental crust.

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