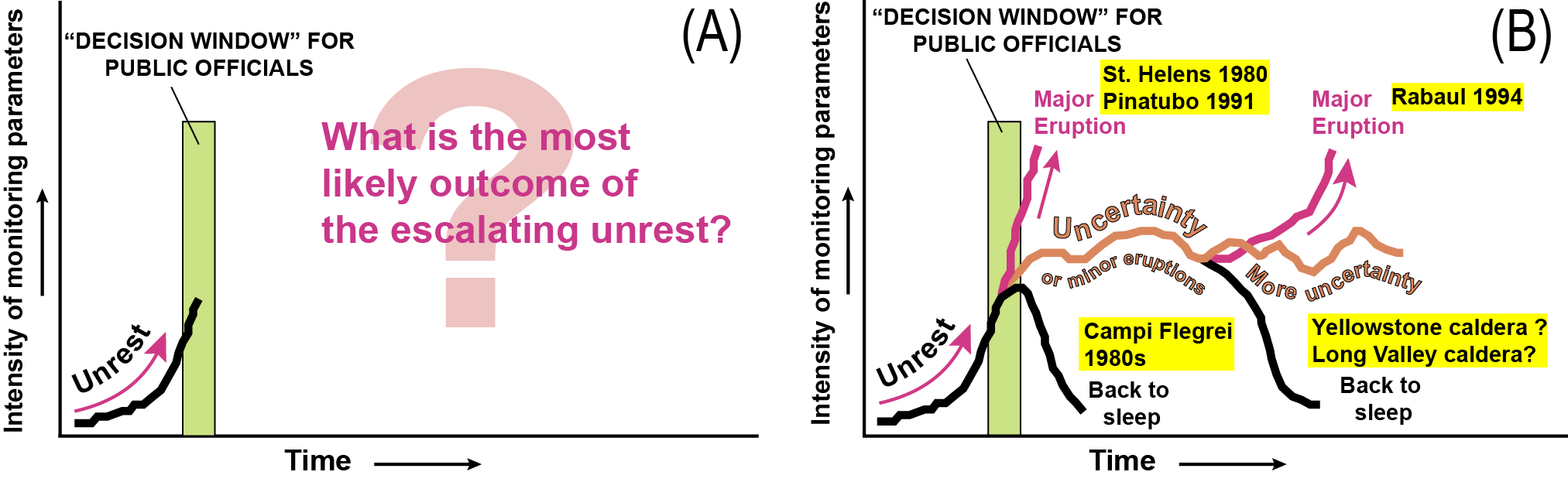
**Volcano science: Future directions from geodesy, radar imaging and physical models**

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Volcanic eruptions have a major impact on society, yet our ability to predict them remains elusive. As magma rises through volcanoes, magmatic processes give rise to changes that can be observed both locally and remotely. Changing magma pressures, driven by magma flow, as well as crystallization and bubble growth, apply forces to the surrounding crust, leading to ground deformation, seismicity, and emissions of gas, ash, and lava from surface vents. These processes are highly non-linear and result in a wide range of volcanic behavior that is difficult to forecast given the limited knowledge of the processes within the volcano interior. However, observations of surface manifestations of the interior processes at sufficient spatial and temporal resolutions, coupled with physical modeling, provide the potential to forecast eruption behavior. This should significantly improve upon our ability to predict volcano behavior, which – despite the considerable risk to society posed by volcanic eruptions – is currently limited to a largely empirical approach based on pattern recognition from sparse *in situ* data and previous experience.



**Figure 1: The high degree of uncertainty of pattern-based forecasting of volcanic behavior during unrest highlights the need to transition into reliable physics-based volcano system understanding and forecasting.** (A) The “decision window” confronting public officials after unrest evolves into a volcanic crisis; generally the most likely outcome of escalating volcano unrest is unknown. (B) Some examples of the actual outcomes of heightened unrest at selected volcanoes (diagram and caption from [*Tilling* [2008](#_ENREF_80)]).

1. Key questions for volcano science

The broad question for volcano science: “How do magmatic systems evolve and under what conditions do volcanoes erupt?” from the “Living on a Restless Planet” report from the Solid Earth Science Working Group (2002), remains relevant and largely unresolved today despite significant progress important components of volcanic systems. The potential with volcanic systems lies in their frequent generation of significant signals prior to eruption (eruption in the broadest possible terms, from “failed” eruptions – intrusions – to long-lasting effusive events). The challenge lies in combining these data into accurate hazard and eruption forecasts (Figure 1; *Tilling*, 2008).

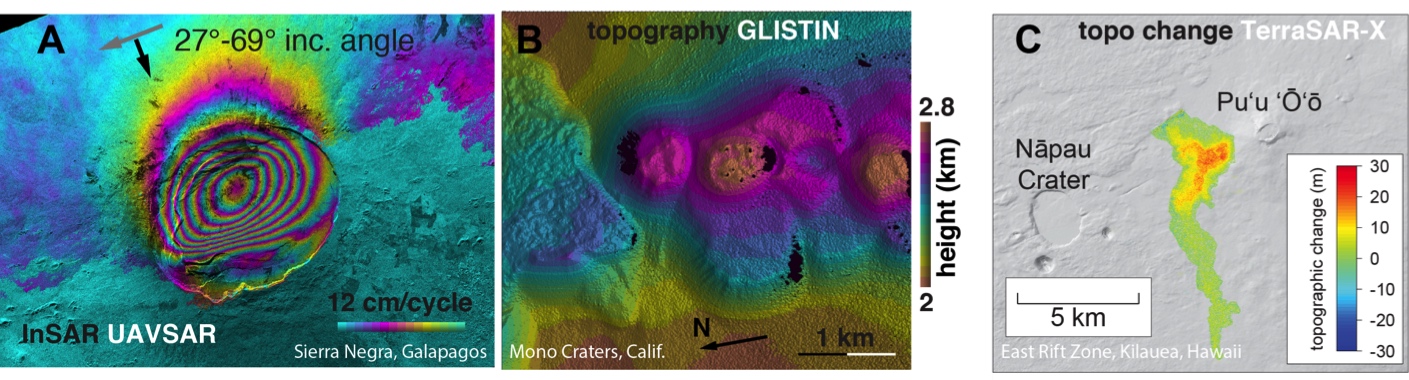
Surface deformation remains one of the key observations for volcano science and monitoring. Over the past 10-15 years increased *in-situ* geodetic measurements, especially from GPS, along with the ever expanding use of interferometric synthetic aperture radar (InSAR) have led to an increasing appreciation of the spatiotemporal complexity of many magmatic systems [*Wicks et al*., 1998; 2002; *Amelung et al*., 2000, 2007; *Pritchard and Simons*, 2002; *Wright et al*., 2006; *Sigmundsson et al*., 2010, 2015; *Riel et al*., 2015; *Lundgren et al*., 2013; 2015]. In particular, InSAR has been critical to identifying previously unknown magma intrusions [*Wicks et al*., 2002; *Pritchard and Simons*, 2002; *Lu et al*., 2002] or previously unrecognized deep sources for nearby active volcanoes [*Lundgren et al*., 2015].

Due to its ability to constrain a number of important properties of volcano mechanical sources, such as shape, location, depth, and volume change, geodesy has thus proven to be an important tool for monitoring and quantifying changes in magmatic systems. However, geodetic observations poorly constrain the total volume of the magma source (reservoir) , do not provide information on the properties of the magma within, and do not quantify the mass or volatile flux out of the system. Given the great complexity and non-linearity of magma fluid dynamics and volcano mechanics many questions therefore remain, including:

* What governs the timing and magnitude of volcanic eruptions?
* What determines the onset, duration, and cessation of shallow crustal magma emplacement?
* Why do some systems continue to inflate through intermittent eruptive activity while other systems erupt with little precursory activity?

Recently, multi-physical (physics-based) time-variable models for volcanoes parameterized by the geometry, rheology, temperature, volatile content, and mass flux of the system have emerged with the potential to both better understand and enable improved prediction of important system parameters such as volume and duration [*Anderson and Segall*, 2011, 2013; *Segall*, 2013]. While geodesy is important for constraining the geometry of the system, petrological, gas, gravity, and erupted volume (topography change) observations constrain properties of the magma and the mass balance of the system (Figure 2). The combination of erupted volume and deformation yields magma compressibility, from which we can infer the magma's volatile content -- one of the most important factors controlling eruptive style [*Anderson and Segall*, 2013].

**Figure 2. InSAR and repeat topography are critical for observing changes in surface deformation and topography change.** (A) UAVSAR interferogram for 2013-2015 inflation at Sierra Negra volcano, Galapagos Islands, Ecuador. The radar viewing direction is indicated by the aircraft heading (gray) and look direction (black) arrows and the ground incidence angle. (B) GLISTIN-A topography of Mono Craters, California. (C) Topography change for the August 2011 lava flow (Kilauea volcano, Hawaii) using TanDEM-X satellite data, which is now reaching the end of its mission [*Poland*, 2014].



1. Timeliness

2.1 InSAR

Recent advances in satellite InSAR, through higher temporal sampling from constellations such as COSMO-SkyMed, TerraSAR-X, and now Sentinel-1A/B (S1B not yet launched) and future missions such as the NASA NISAR mission will greatly improve the spatial and temporal coverage critical for global geodetic observations at spatiotemporal sampling that will provide critical geodetic constraints on time-varying volcano geometric source parameters. In addition, a number of recent and potential future advances in radar imaging of topography change and magma source locations and volumes, coupled with emerging multispectral remote sensing, are poised to provide additional observations critical to constraining physics-based dynamic source models.

2.2 Topography

Topography change observations have been achieved through the German Aerospace Center (DLR) TanDEM-X mission (Figure 2C), but that mission will not be available in the future. A new NASA airborne instrument, GLISTIN, designed for ice and land topography change measurements, flies on the NASA G-III and uses two side-by-side Ka-band radars (1 cm wavelength) to generate single-pass digital elevation models (DEMs). In future volcano crises GLISTIN topography change observations could be used to generate mass flux observations to constrain physics-based models.

2.3 Volume

Rayleigh-resonance (RR) radar imaging is a newly emerging method that may allow us to directly image magma reservoirs in the upper crust (~upper 5 km). Though still a theoretical concept, if proven, it has the potential to revolutionize volcano science.

RR imaging uses the scattering of electromagnetic waves in the Rayleigh and resonance regime [*Kleinman,* 1965; *Jackson,* 1962], instead of high frequency pulses in sounders, to image magma within volcanic systems at large depths beneath the ground. The Rayleigh region is well known to contain volume information of a scattering body, whereas the resonance region is known to contain shape or area information of a scattering body [*Jackson,* 1962]. The technique to image using the Rayleigh-resonance scattering has been formulated in the past to enable volume imaging of bodies in free-space or air using a time-domain ramp waveform, instead of a pulse as used in sounders and traditional radars [*Young,* 1976]. The purpose of the ramp waveform is to emphasize the low-frequency scattering of the body, thus emphasizing the Rayleigh-resonance scattering [*Chen and Peters,* 2007; *Young,* 1976]. The low frequency nature of the technique permits much deeper penetration than traditional sounding radars.

1. Need for space- and airborne-based observations

Volcanoes span the globe, located in both remote and densely populated locations. To advance volcano science and hazard mitigation requires observations that are global and of uniform quality, although targeted airborne, and *in-situ* observations at select, high-value locations will also drive scientific progress. This requires remote sensing observations from a trio of radar techniques to provide the required surface deformation, topography change, and reservoir shape and volume: repeat pass InSAR, single pass InSAR, and RR radar imaging.

3.1 Surface deformation

Repeat-pass InSAR is the most robust with existing and planned satellite missions from a number of space agencies, including the future NASA NISAR mission. In addition, the NASA UAVSAR L-band airborne instrument can provide surface deformation observations at high resolution from arbitrary viewing geometry and time sampling, thus providing an important complement to satellite InSAR, especially during volcano crises. Due to the wide temporal bandwidth of volcano processes future volcano science will increasingly benefit from higher temporal sampling of surface deformation, especially during major volcano crises, such as exponentially inflating explosive volcanoes and major rifting or diking events.

3.2 Topography change

Topography change from single-pass (i.e. tandem) satellite (TanDEM-X) or airborne (NASA GLISTIN) provides all-weather, day-night capabilities to measure topography change. The NASA GLISTIN system could be deployed to measure lava effusion volumes and topography change during both extended volcanic eruptions and shorter duration volcano crises. A new satellite tandem system beyond TanDEM-X is required to provide global access with regular acquisitions, although an airborne system such as GLISTIN would allow for the most frequent and highest resolution observations required during large volcano crises.

3.3 Magma volume imaging

The RR radar technique can be used on an airborne or low-orbiting satellite platform to enable volume imaging of deeply embedded bodies for the following reasons: (1) Scientific observation/imaging of deeply embedded bodies, such as aquifers and magma reservoirs, which cannot be directly observed today, can have sizes, *𝑠*, on the order of many hundreds of meters to a few kilometers; (2) The large sizes of these bodies, and due to RR requirements of *𝑠~𝜆* (wavelength), imposes RR radar frequencies on the order of a few hundred kilohertz; (3) The low frequencies required by the RR radar for these bodies penetrate with low loss into conducting ground, which enables remote sensing to substantially lower depths than previously possible with sounding radars; (4) The RR radar technique does not require synthetic aperture radar techniques to perform imaging, and can instead obtain volume imaging from as little as a few looks (three or more looks). When using synthetic aperture, it would be expected to obtain much higher resolution volume images than possible with traditional RR imaging. Validation of this technique will enable a new class of NASA missions that permit science-focused imaging of magma bodies within volcanic systems. In addition, the validation of the technique will also have an impact in potential missions to map aquifers and other large bodies that are located too deeply for traditional sounder technologies. Beyond NASA there are potentially additional benefits for mapping deeply embedded bodies in general, where traditional radio-based techniques fail.

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