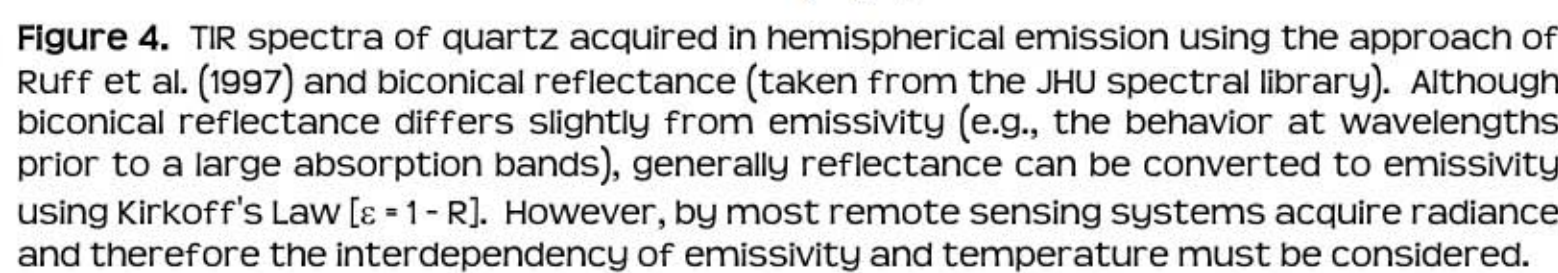


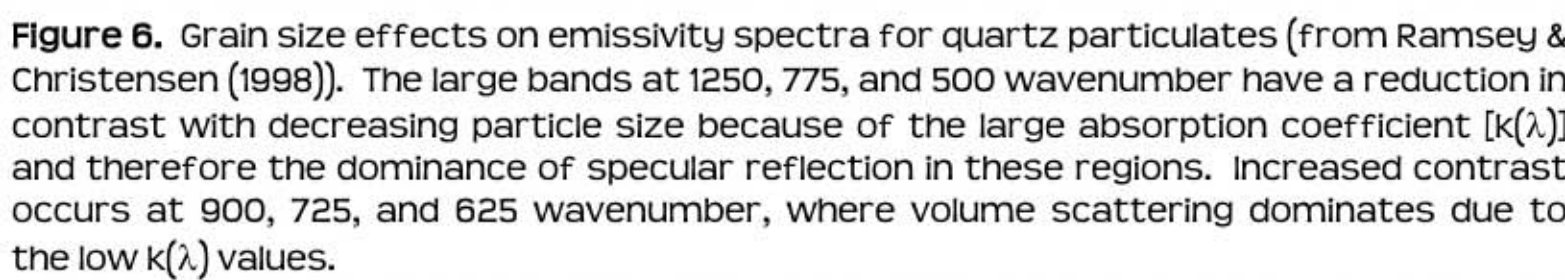


Infrared emissivity is a fundamental property commonly used to identify the composition of planetary atmospheres and surfaces. For a material with an emissivity of unity at all wavelengths (aka "a blackbody"), the emitted radiance follows a Planck distribution (Eqn 1) and is the maximum possible for a given temperature (Fig 1). However, vibrations in the atomic structure of most materials give rise to discrete regions where the emissivity is less than one (Fig 2). Emissivity therefore can be defined as the fractional representation of the amount of energy emitted from a surface at a given temperature compared to the energy from a blackbody at the same temperature. These absorption bands have been used for decades to identify the constituents of the emitting surface whether in the laboratory, the field, from the air, or from orbit (Fig 3).

Where trying to measure emissivity uniquely, one must also know the surface kinetic temperature (or the emissivity at one wavelength). This constraint has been largely overcome by a variety of techniques including detailed laboratory calibration or measuring the infrared reflectance, which is inversely related to the emissivity and much less dependant on temperature (Fig 4). Once measured, numerous modeling approaches have been developed to deconstruct the emissivity spectrum in order to extract other properties such as compositional mixing (Fig 3), thermal inertia (Fig 5), and grain size of the surface (Fig 6). These rely on the assumption that emissivity, where sampled accurately, remains unchanged from measurement to measurement.



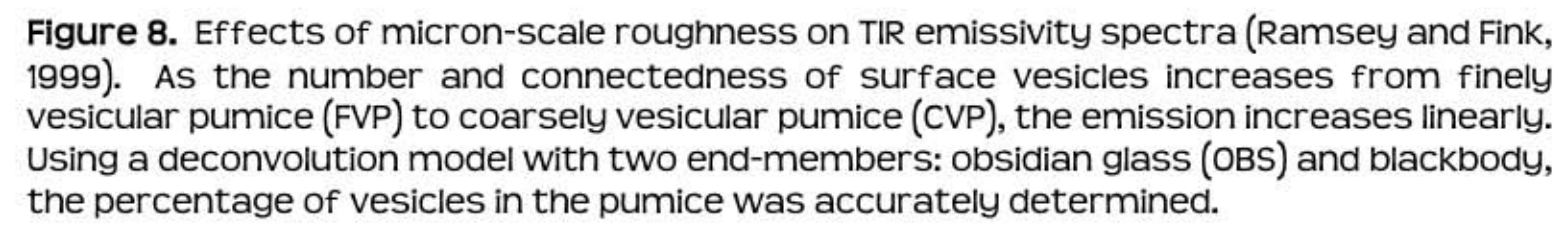
The assumption of immutable emissivity has been shown to be false for certain situations and in fact may not be strictly true for many remote measurements. For example, surface coatings (Fig 7), temperature gradients/mixing, and particle-size variations (Fig 6) (all common in planetary applications) dramatically alter the emissivity spectrum of common minerals.



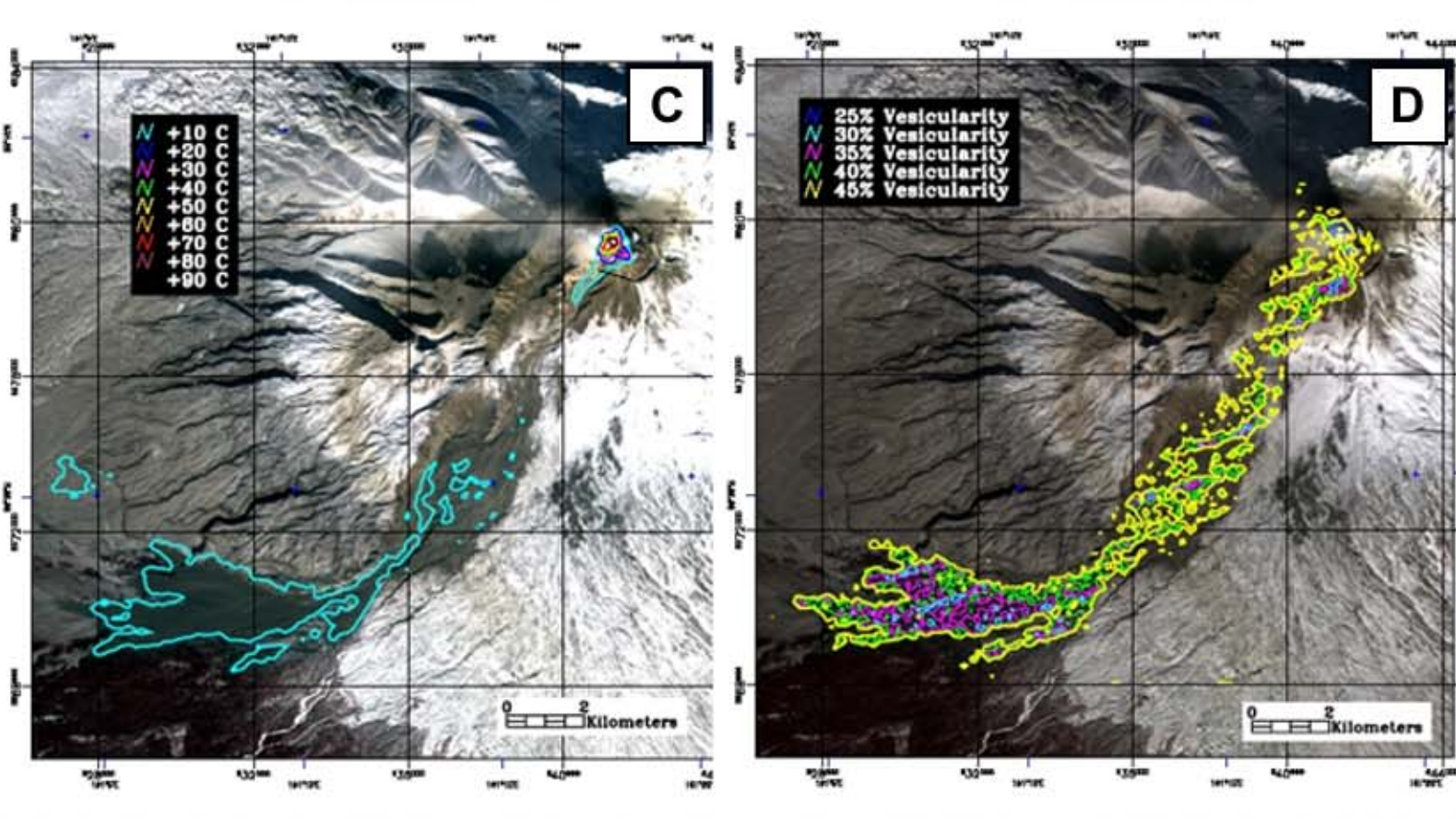
**Figure 7.** Effects of surface coatings on the spectra of granodiorite (from Christensen and Harrison 1993c). Increasing thickness of desert varnish reduce the spectral contrast of the large absorption band 1150 wavenumber. The thickest coating (light line) was ~ 28 microns and resembles the spectrum of montmorillonite clay. The linear relationship between coating thickness and spectral feature contrast means the spectral mixing was similar to "checkerboard" rather than an attenuation through an absorbing layer.

More recently, micron-scale surface roughness or cavity radiation at larger roughness scales has also been shown to decrease the contrast of the emissivity features. This effect has been used to model the percentage of vesicles in extrusive/explosive volcanic products (Figs 8 & 9) and to understand better the importance of surface topography using radiosity models (Figs 10 & 11).

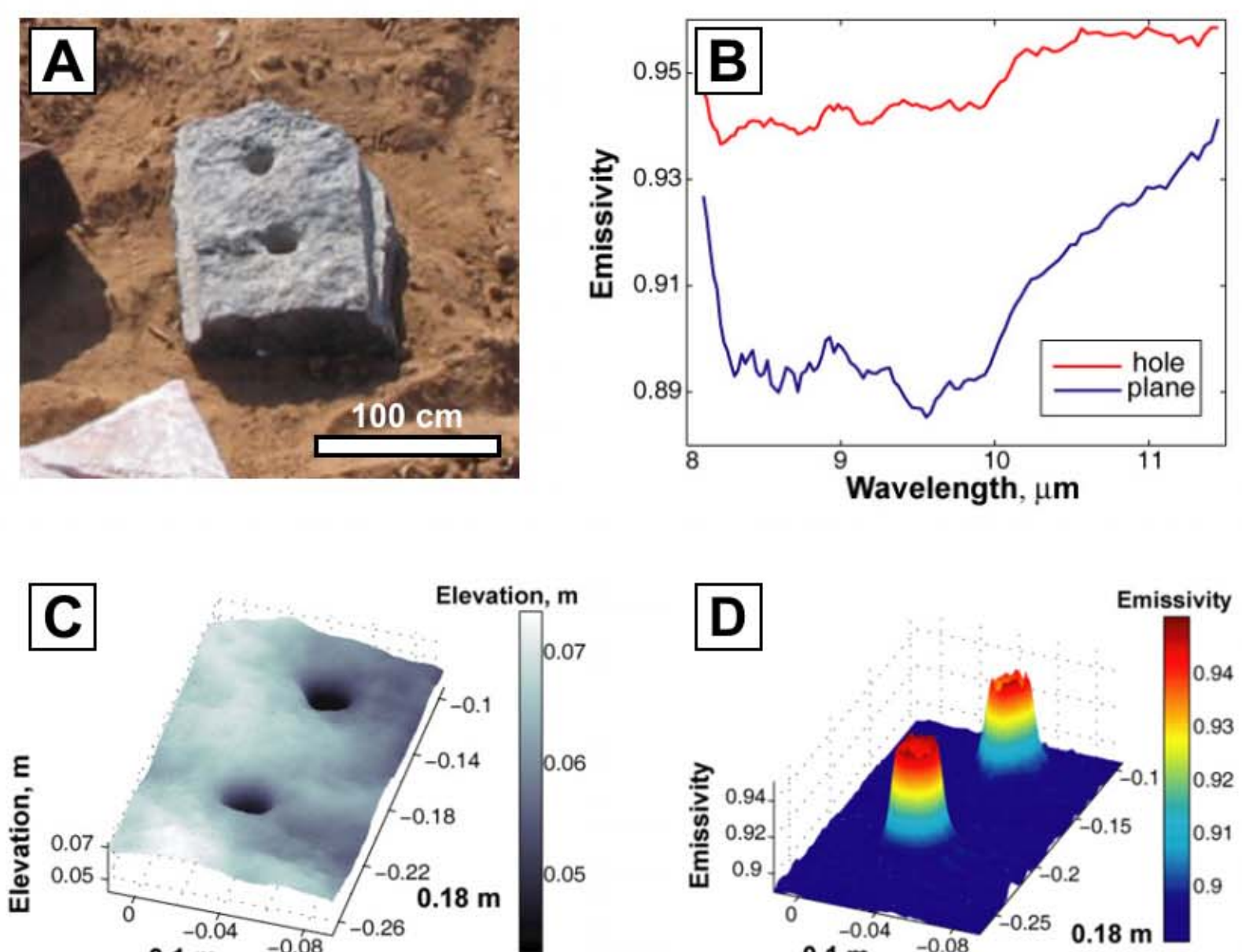
Furthermore, for measurements made over thermally heterogeneous surfaces, the non-linear mixing of temperatures will greatly alter the final emissivity spectrum making both quantitative analyses and accurate correction difficult. This was observed by Abtahi et al. (2002) on active flows in Hawaii (Fig 12). The question of whether this lowering of emissivity was a real phenomena or a result of the "Planck Effect" was resolved to some degree by using a thermal IR camera and the collection device (Fig 12). However, small-scale temperature variations due to crust formation, etc. could not be constrained using this measurement approach. This uncertainty was later resolved by Lee and Ramsey (2011) using a novel micro-furnace to track the change in emissivity with temperature (Fig 13).



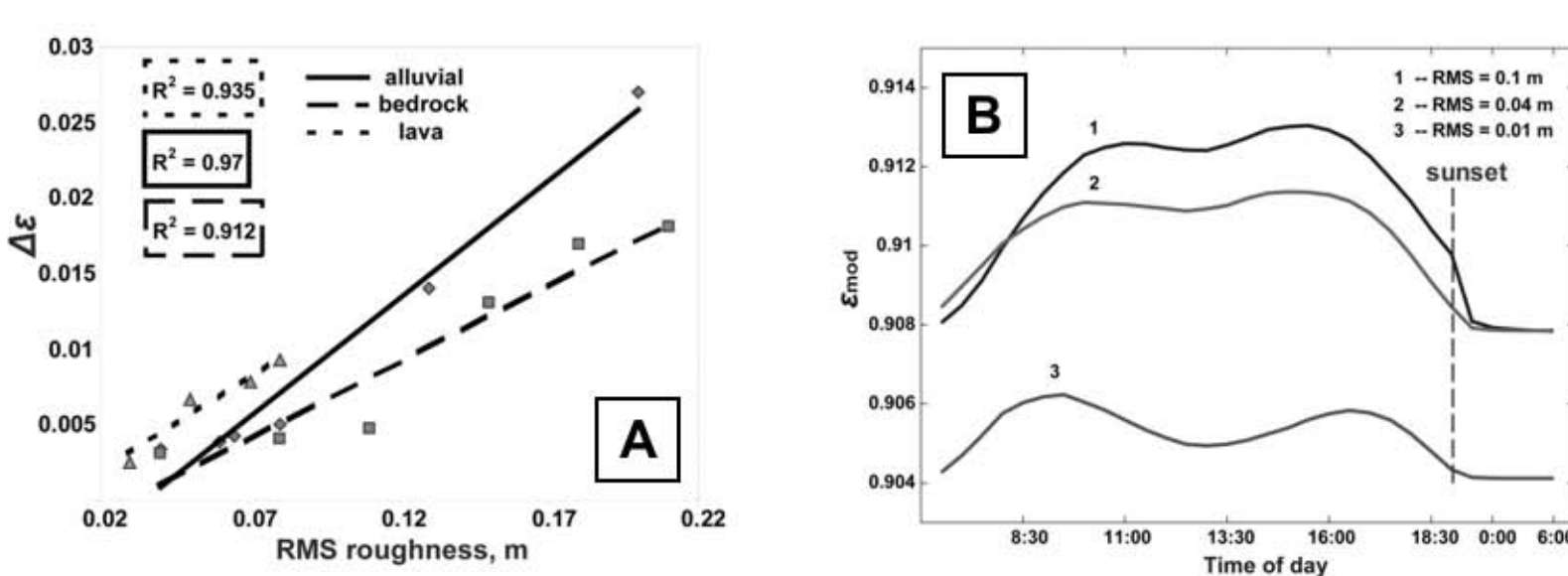
**Figure 8.** Effects of micron-scale roughness on TIR emissivity spectra (Ramsey and Fink, 1999). As the number and connectedness of surface vesicles increases from finely vesicular pumice (FVP) to coarsely vesicular pumice (CVP), the emission increases linearly. Using a deconvolution model with two end-members: obsidian glass (OBS) and blackbody, the percentage of vesicles in the pumice was accurately determined.



**Figure 9.** Surface temperature and modeled surface vesicularity changes derived from ASTER TIR data acquired in March 2005. Note the reduction in surface vesicularity of the pyroclastic flow deposit over the two-week period. [A] Helicopter-based photograph of the 27 February 2005 pyroclastic flow deposit (taken by M. Ramsey on 25 August 2005). [B] 12 March 2005 vesicularity. [C] 29 March 2005 temperature. [D] 29 March 2005 vesicularity.

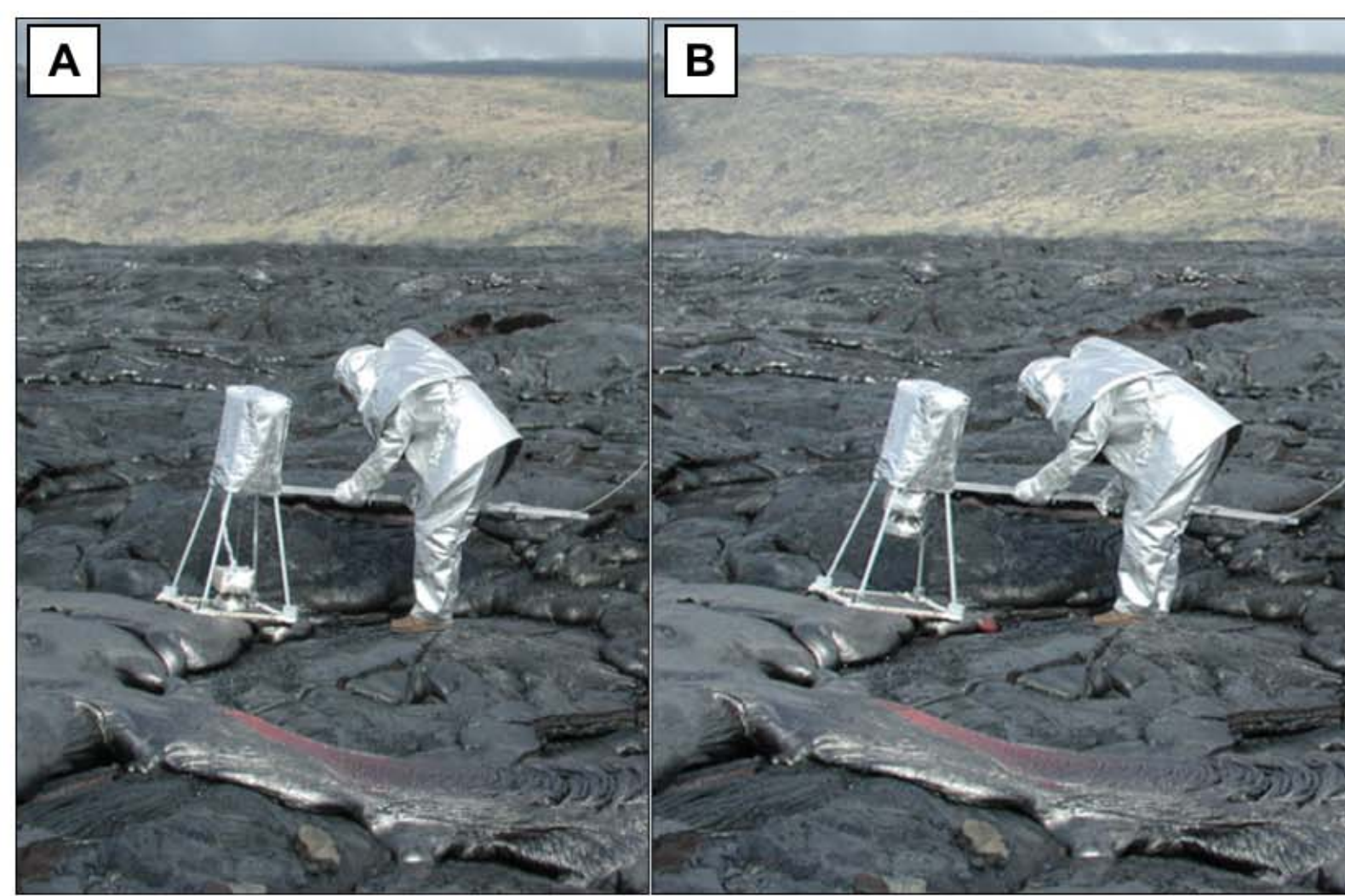


**Figure 10.** Impact of surface topography on derived emissivity. **[A]** Norite rock with two drilled holes. **[B]** Field-based emissivity spectra of the rock using a TELOPS Inc. HgCdTe imaging spectrometer (note the reduction in spectral contrast). **[C]** Micro digital elevation model (DEM) of the rock's upper surface. **[D]** Change in the derived emissivity due to the blackbody effect is easily modeled.

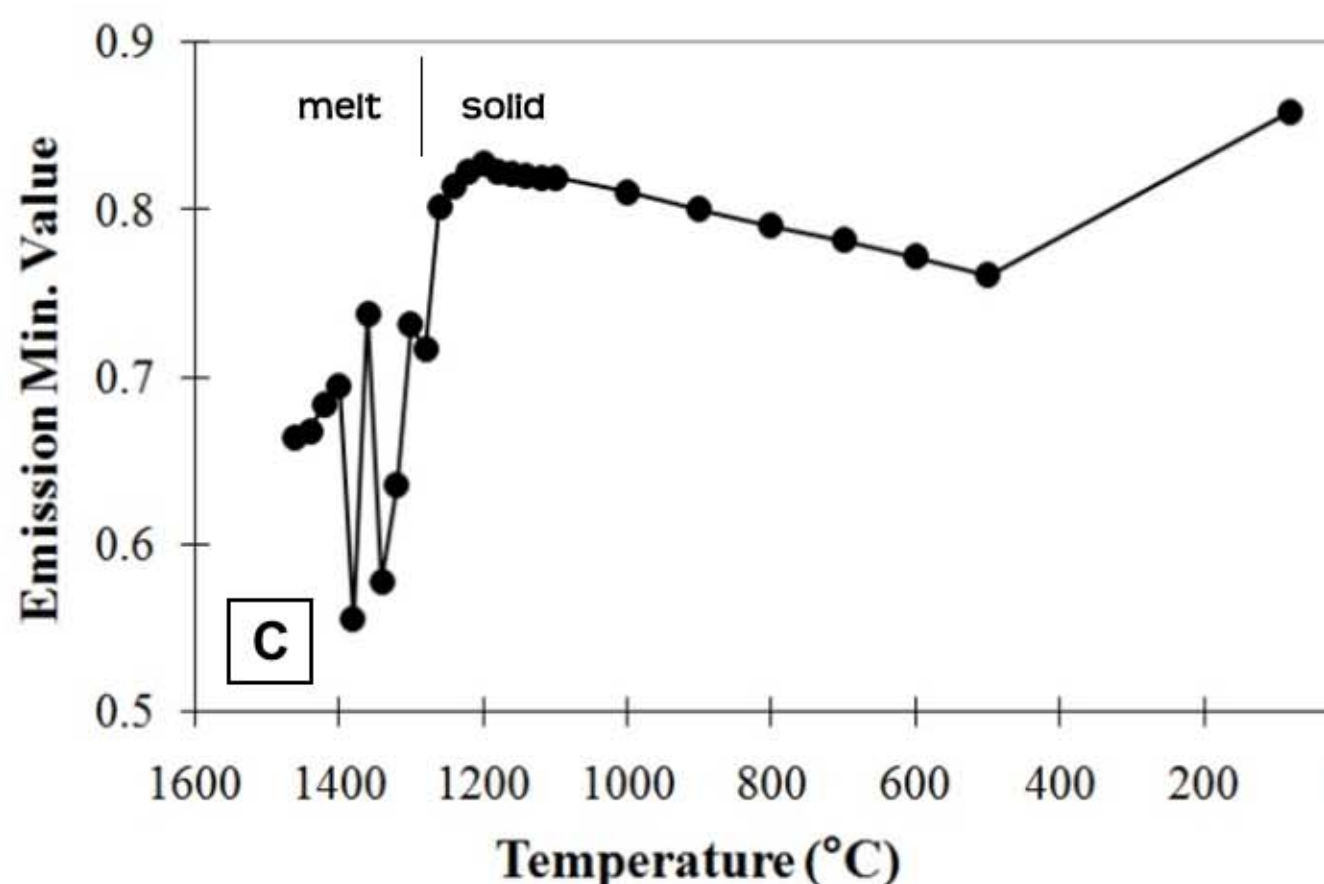
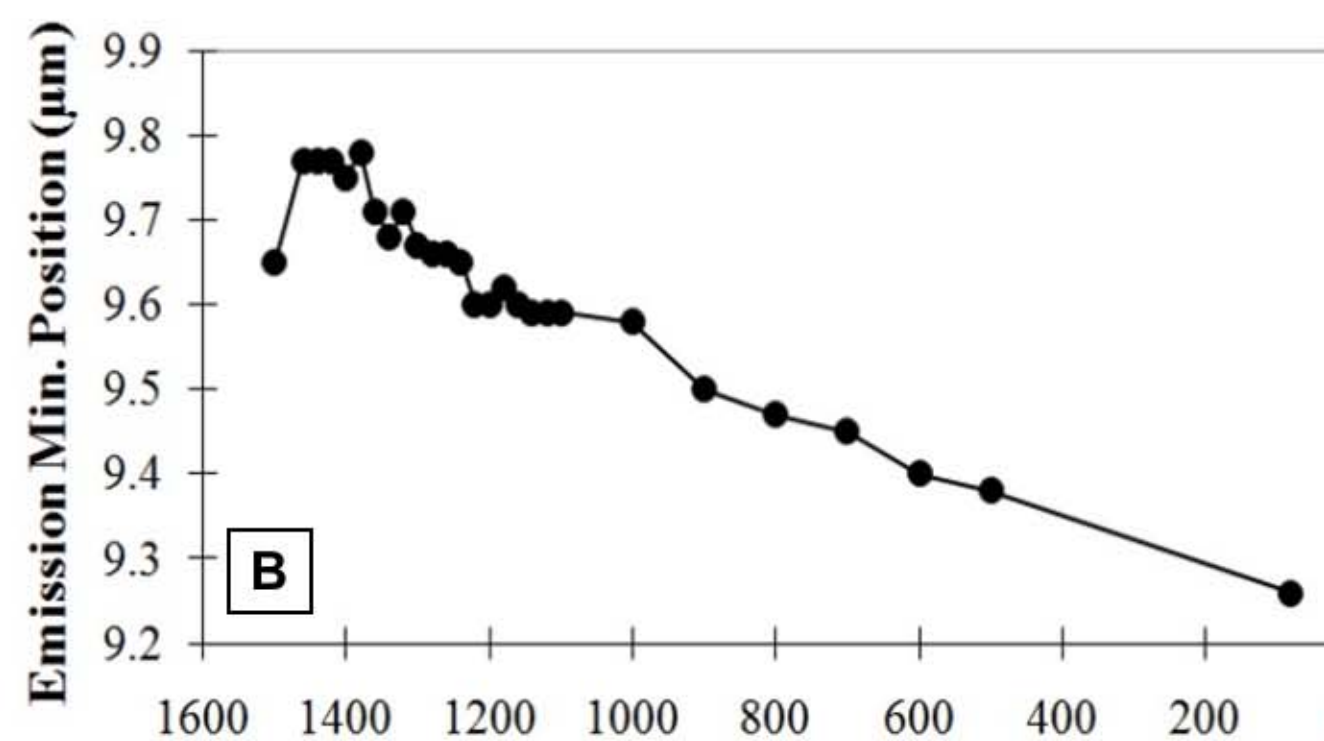
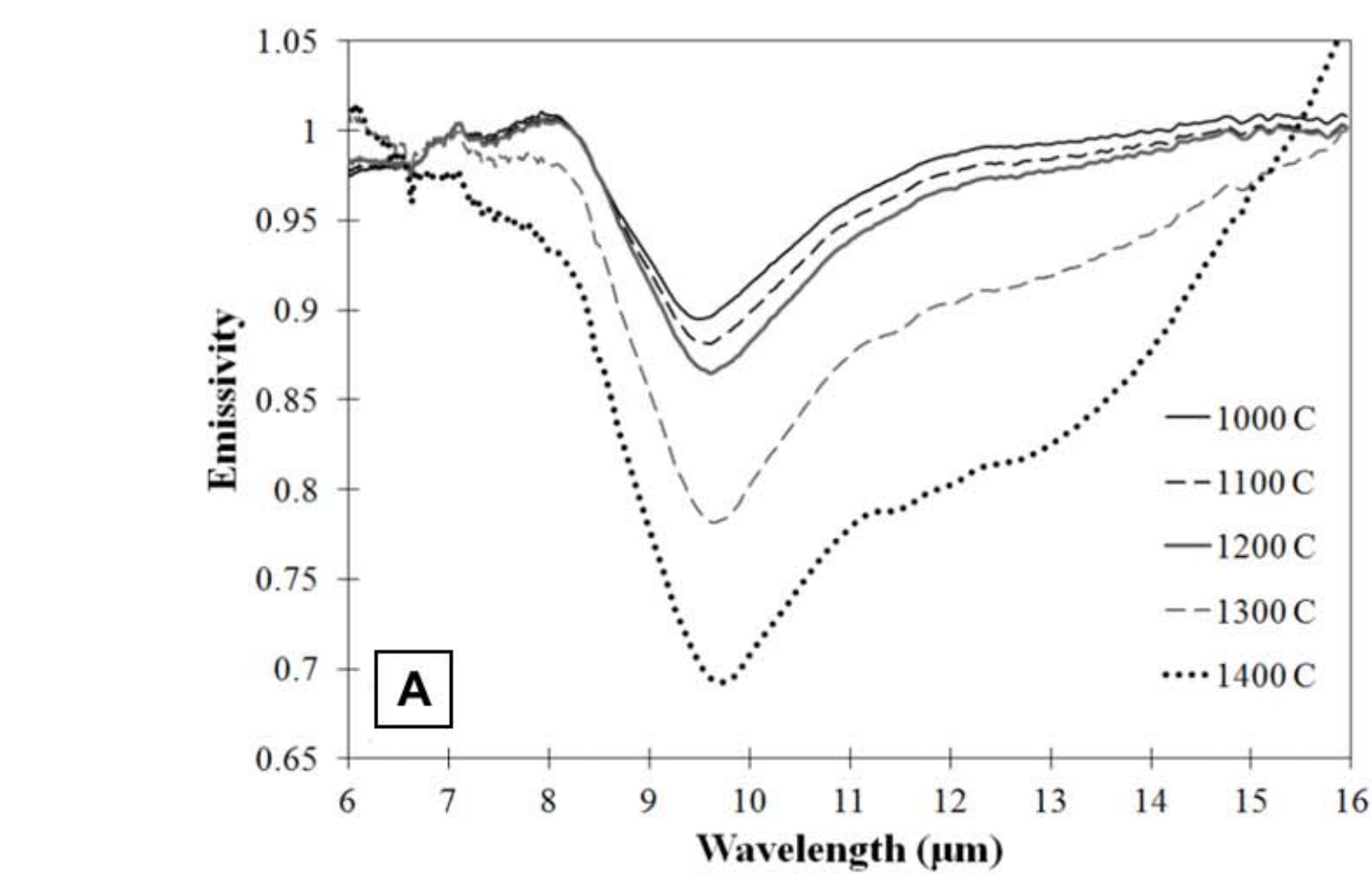


**Figure 11.** Effect of surface roughness on  $\Delta\epsilon$ . [A] Change in emissivity for alluvial ( $\diamond$ ), bedrock ( $\square$ ), and lava flow ( $\triangle$ ) surfaces. Value of  $\epsilon$  used for the model calculations was 0.9,  $T = 300\text{ K}$ . [B] Radiosity model of emissivity averaged over the course of a day for alluvial surfaces of different roughnesses in Death Valley. Note different time step after sunset (Danilina, 2011).

Research by the authors into the response of emissivity with large temperature changes has verified the dramatic variability that occurs with a change of state (i.e., a structural phase changes as the material begins to melt). Furthermore, small-scale changes may arise even at much lower temperatures, calling into question the accuracy and interpretability of emissivity at the percent level. Data from the laboratory, field, and future TIR sensors (e.g., HypsIRI) should be carefully inspected prior to interpretations of TIR emissivity and temperature.



**Figure 12.** In-situ measurements of emissivity on molten basalt in Kilauea, Hawaii (Abtahi et al., 2002). **[A]** Measurement device consisting of an FTIR instrument mated to a hemispheric collector (electronics are housed in the upper part). **[B]** instrument prior to deployment. **[C]** Spectra showing progressive decrease in emissivity at longer wavelengths with increasing temperature. **[D]** Broadband emissivity of all spectral measurements versus temperature.



**Figure 13.** Results from the in-situ melting and laboratory spectral acquisition of a synthetic glass mixture (Ab50 + Qtz). **[A]** With increasing temperature, the emissivity is depressed by more than 35%. **[B]** The emissivity minimum position shifts nearly linearly to longer wavelengths with temperature. **[C]** The emissivity minimum value also follows a linear increase with temperature until the liquidus temperature ( $\sim 1350$  °C) (from Lee et al., 2012).

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