Cinder Cones, Canyon de Chelly, 1998

The first question to be asked about the Springerville volcanic field is "Why is it here?" To explain this we need to know a little bit about the history of the Colorado Plateau and surrounding terrain.

Subduction of a plate at the Western continental margin has led to two major episodes of mountain building in the past 100 My. Most of the western US experienced high levels of deformation. The Colorado Plateau did not. It was relatively stable against these high stresses. Rigidity against stress is provided by the crust and uppermost layer of the mantle. Beneath this layer the mantle is too hot and weak to withstand stresses. Geologists call this rigid top layer of the Earth the lithosphere. The Colorado Plateau rested on top of a relatively cool and thus even more rigid section of lithosphere. Before, during and after the deformation the Colorado Plateau lay close to sea level, not at the 2km height at which it now stands.

After the mountain building ceased 20 My ago or so the Plateau began to be uplifted by events in the mantle. Upwelling magma reached the bottom of the crust and cooled to form more floating low density crust. This increased the crustal thickness from 30km to 45km and gave an uplift of about 1 km. In addition to this thickening, the lithosphere began to get hotter. Thermal expansion led to another km of uplift. The uplift due to heating is not yet over. Measurements of heat flow and temperature suggest that the Plateau will be uplifted some more before it stops. I haven't got any data to quantify the future uplift.

While this is going on the Basin and Range Province is being formed by extension. We identify the two regions by their different physiography, or surface features. The Plateau contains horizontal, undeformed sedimentary strata whereas the Basin and Range province contains regular, long, parallel mountain ranges and intervening basins. The valleys are broader than the ranges and the valley floor elevation is low. The Plateau Margin province has characteristics of both provinces with narrow valleys.

Figure 1 shows the major physiographic provinces of the western US. It omits the Plateau Margin. Figure 2 shows the Plateau Margin or Transition Zone on a smaller scale map. We'll come back to the details on this figure in a moment. Figure 4 shows the topography of the Plateau Margin. The Springerville Volcanic Field is the slightly bumpy region between Show Low and Springerville.

The physiographical boundary between two regions is not necessarily the same as the geophysical boundary. The geophysical boundary is defined by seismic velocities, heat fluxes, crustal thicknesses, etc. This lies ~50 km into the Colorado Plateau, away from the physiographical boundary. The physiographic boundary is pretty much fixed in the position it was at formation, except for erosion. It is conceivable that the geophysical boundary could be shifted by mantle processes. Were the two boundaries once coincident? We'll see a little bit of evidence for and against this argument but it isn't something we'll go into in detail.

The large (~50%) change in crustal thickness between the two provinces generates a stress field at the margins. This stress field is what opens up cracks for the magma to rise up and cause volcanism at the surface.

We are standing in one of those volcanic regions right now. On figure 2 the Springerville Volcanic Field is dead centre. Shaded fields are younger than outlined fields and you can see a trend for volcanism to move into the Plateau from the margins over the past 15 My. Is this caused by the geophysical boundary marching into the Plateau over time? Some people used to think so, a more recent paper thinks not.

Figure 3 shows a few of the volcanoes in the field. They are all a certain type of volcano called a "cinder cone". There are 400 of them in this field. A cinder cone is a type of volcano formed by the eruption of very gassy, quite viscous lava. The pressures in the magma have superheated the gas so that when it escapes to atmospheric pressure it expands significantly and blows rock, lava and volcanic glass fragments from the vent. This material ranges in size from dust to 10s of cm.

The ejecta shoots up in the air and comes back down. When it falls it forms a cone. The sides of the cone are very steep (~30'). This angle of repose is controlled by friction between the ejecta (just like a heap of sand). The smaller particles are blown the furthest from the vent and form the base of the cinder cone. Their different size gives them a shallower angle of repose (~10'). This accounts for the characteristic shape of cinder cones.

Cinder cones are usually small, less than 1 km in diameter and 300m in height.This is because they have only one eruption period. When the magma supply rateto a volcano is low (as it is here) conduits are not maintained in the crust and individual magma batches ascend by different pathways rather than all flowing in the same conduit.

This means that cinder cones frequently form as groups or as parasites on larger volcanoes.

What can we observe by simply staring at these volcanic features?
1) Variable crater size - controlled by the explosivity of the gas in the final stages of the eruption.
2) Spatter ramparts - a lava fountain towards the end of the eruption can deposit molten ejecta on the cone, modifying its shape by emplacing ramparts of spatter.
3) Lava flows - if the gas content drops lava may flow out of the cone, modifying its shape.

Figure 5 shows a schematic of a cinder cone and figure 6 shows an aerial view of a cinder cone in the San Francisco Volcanic Field (figure 2) to the west of here. The lava flow in figure 6 originated at the base of the cone so has only slightly modified the conical shape.

As the cones are made of unconsolidated material they are easily eroded. They become less steep with time as loose material is transported down the flanks. After 3- 4 My only the central dike of solidified magma remains.

The Springerville Volcanic Field contains only cinder cones without any other types of volcanoes. This is unusual compared with the other Plateau Margin fields. In addition to cinder cones they form volcanoes characteristic of higher magma supply rates.

There is ~2500km2 of volcanic outcrop and ~300km3 of extruded rock in the field. Almost all of the 400 cinder cones are <2.1 Myo, making the field young and minimizing the range of erosion states present in the field. The youngest cinder cone is 300,000 years old. This age is 100x the mean interval between eruptions in this field, suggesting that the volcanism may have waned or ceased completely. This is not the case in all the Plateau Margin Volcanic Fields. In the San Francisco Volcanic Field the last eruption was 750 years ago and another one is expected in the next few thousand years.

Now for the hardcore geology details...

This lava is basaltic - i. e., igneous rock, rich in Mg, Fe, that crystallized at pressures close to surface rather than deep in the bowels of the Earth.
Basalts are 47 - 52% SiO_2 and commonly contain the minerals plagioclase, pyroxene and olivine.
Plagioclase = $NaAlSi_3O_8$, $CaAl_2Si_2O_8$ (Alkalis and Al)
Pyroxene = $M^{2+}SiO_3$, where M^{2+} = Mg,Fe,Ca
Olivine = $(M^{2+})_2SiO_4$, where M^{2+} = Mg, Fe

The basalt family is further subdivided.
Basalt with lots of olivine and lots of Ca-pyroxene is called Alkali Olivine Basalt.
Basalt with little olivine and little Ca-pyroxene is called Tholeiite.
Basalt which falls between these two categories is called Olivine Tholeitte.

By volume, the lava is 47% AOB, 28% hawaiite (basically AOB with more SiO_2 and more alkalis) and 24% tholeiite. (The tholeiite was erupted in a few large events.)

The effusion rates of these three lavas throughout the lifetime of the field are shown in figure 7. The peak effusion rate is 1 to 2 orders of magnitude lower than in most basaltic volcanoes, accounting for the formation of cinder cones.

Tholeiite was dominant between 2 and 1.75 Mya.
AOB was dominant between 1.75 and 1.0 Mya.
Hawaiite was dominant between 1.0 - 0.3 Mya.

What can we infer from this?
It is consistent with:
Early vigourous upwelling and lithospheric melting which would produce tholeiite, followed by deeper, less vigourous asthenospheric melting which would produce AOB.

The sites of active volcanism have migrated eastward over time. Velocity 2.5+/-0.8 cm yr^{-1} on a bearing 106+/-13' over the past 2 My. Similar results are found at the San Francisco Field. This is consistent with the westward motion of the North American plate over a fixed magma source in the mantle. It is evidence against the geophysical boundary marching into the Plateau, but note the different timescales, 2 My not 15 My.

There is no obvious alignment of the vents. In other fields vents have a tendency to line up on the faults but there are no faults in this region. There may be some lining up parallel to the Mogollon Rim but it is not very distinctive.

Points to Remember:

Cool lithosphere prevented deformation of the Colorado Plateau.
Plateau then uplift by heating and crustal thickening.
Crustal thickening leads to stresses and volcanism around Plateau Margin.
Low effusion rate of basaltic lava formed cinder cones in Springerville Field.
These are small, steep sided and easily eroded.
Vents migrated eastward due to motion of plate over fixed source in mantle.
This field likely to be extinct but others still active.

This bit could be chopped. Leave it at the end as a filler if needed.

One of the few volcanoes whose formation has been observed from beginning to end is a cinder cone.

In 1943 a small Mexican village experienced two weeks of mild tremors. One day a farmer was out in his fields when he saw sulphurous smoke billowing from a small hole in that had been in the field for as long as he could remember. That night glowing ejecta from the hole produced a spectacular fireworks display.
After 1 day the cone grew to 40m high
After 5 days the cone grew to over 100m high and was ejecting fragments to a height of 1 km.
Within two years the cone had attained its full height of 400m.
6 months after the initial eruption, a lava flow pushed its way out of the base of the cone and began to roll slowly towards the village, eventually engulfing it.
After 9 years all activity ceased and Paricutin fell silent, probably for ever.

1) Thompson, G.A. & M.L. Zoback; Tectonophysics v61 (1979) 149-181
2) Connor, C.B et al; JGR v97 #B9 (1992) 12349-12359
3+4) Condit, C.D et al; http://www.geo.umass.edu/faculty/condit.html
5) Sheridan in 'Landscapes of Arizona', ed. Smiley et al (1984)
6) Wolfe in 'Landscapes of Arizona', ed. Smiley et al (1984)
7) Condit, C.D. et al; JGR v94 #B6 (1989) 7975-7986

These articles were also the main sources for the text of this presentation.