Cinder Cone or Mud Volcano?

Experience Bias and Observation on the Papuan Plateau

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My grandfather once said to me that "sometimes I sits and think, and sometimes I just sits." In the Covid Anthropause one might be forgiven for adopting the latter strategy – but the questioning mind of the geologist is built for puzzle solving, as demonstrated in a recent debate on LinkedIn about a curious geological puzzle.

The image below was recently posted on LinkedIn by Discover Geoscience (Searcher's G&G team). They asked: "*Cinder Cone or Mud Volcano? We discovered this bad boy lurking in Searcher's Hahonua Dataset while working on our regional Gulf of Papua Regional Study recently. What do you think it is?*

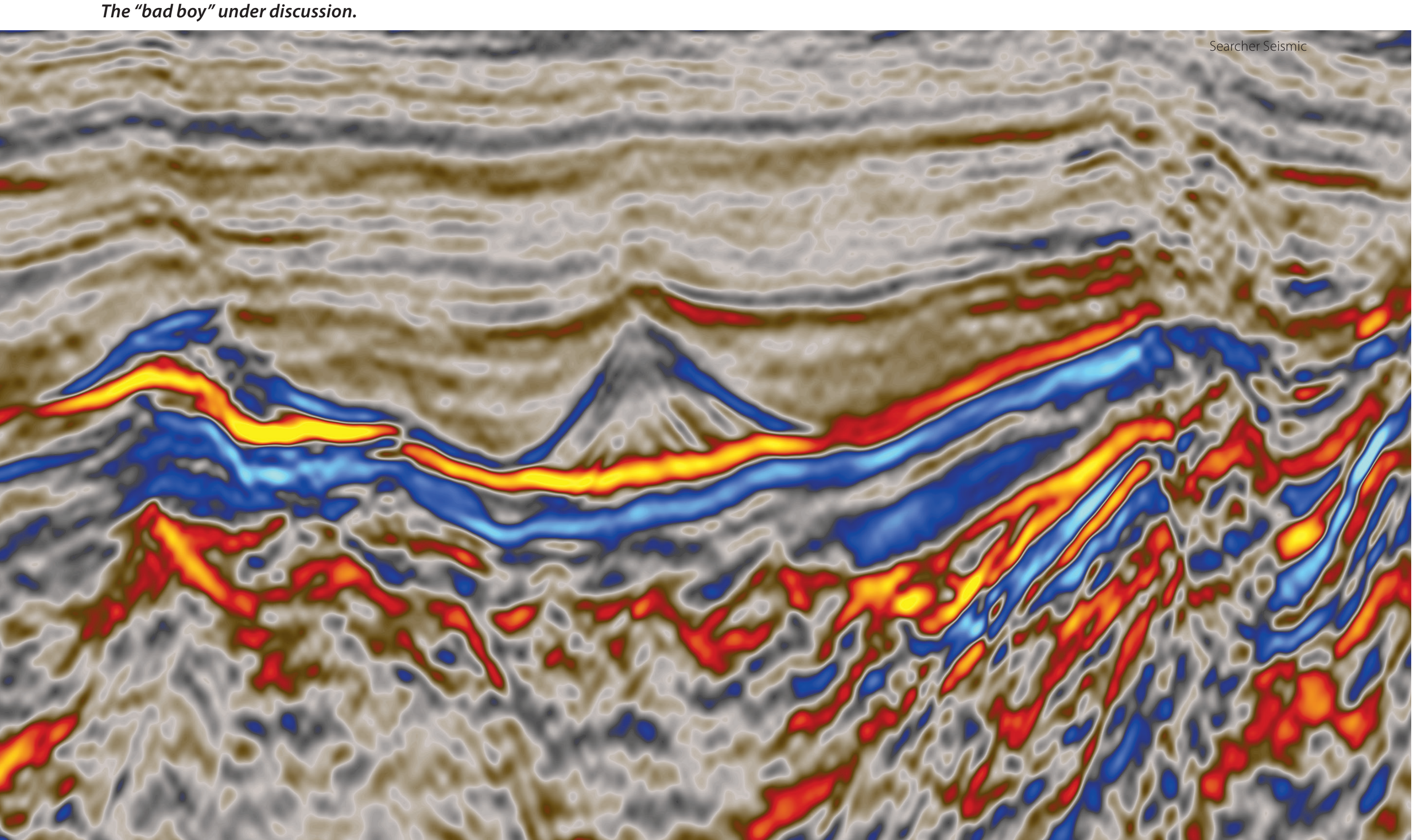
"It sits on a regional flooding surface above a small half graben with no obvious vertical feeder pipe below. It is 130m high by 1km wide and looks identical on the crossline. There are known volcanics at this time regionally, but the basin was also likely maturing for hydrocarbons at the time. Is it a gas escape feature or volcano?"

The "bad boy" in question is the beautifully-imaged nearly equilateral triangular structure at the center of the image below, which we will now call the 'feature'.

In the 21st century, this should be a simple question; a clear, modern seismic example of a distinctive feature, many of which have been described and seen before. But this is geoscience, and we look for both "what are we seeing?" and "how did it get there?" to tell us what it is made from and whether it has utility. This is deduced from a huge variety of potentially uncertain observations, with their alternatives and subtleties. Weighting of this information can and does create a diversity of interpretation. The debate on LinkedIn drew many responses, from all over the globe. Some geoscientists were obviously intimate with the area and some less familiar but had a great line in observational reasoning. However, given a binary question, what was interesting was the range of strongly held conclusions that were distilled from the available information.

Some responses were simply: "it's a cinder cone" or "it's a mud diapir"; observations made from experiential analogy (aka "seen this before bias"), or perhaps based on the click-bait quick look. As Malcom Gladwell showed in his book *Blink*, reflex analyses can be helpful and insightful, but since as many jumped one way (igneous volcanic) as the other (fluidized sediment) by reflex, we needed a more reductive analysis to move ahead. So started the more observational analysis. Of course, before you can put a geologist in a box with only two sides, first you need some "but is it either?" suggestions.

The "bad boy" under discussion.



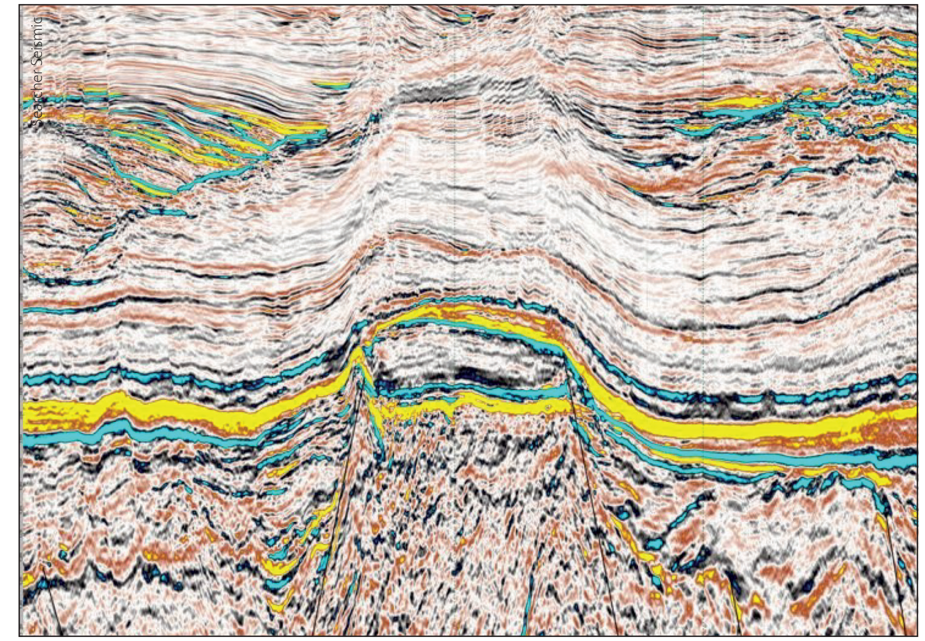
Carbonate Build-Up?

An alternative to seabed extrusion of one form or another is the suggestion that the feature is a carbonate build-up. Pinnacle reefs are well known in the Gulf of Papua, and Luis Carlos Carvajal made the excellent suggestion that we use the Burgess et al. (2013) 20-step observational ranking methodology to analyze the feature as an isolated carbonate build-up. In this system the feature scored 5 out of 20, suggesting that either the ranking system was not attuned to this type of carbonate build-up or it is not one.

A characteristic of a carbonate between overlying and underlying mudstones is a hard seismic kick in the acoustic impedance at the top of the feature, with a soft one at the base. Here, the blue dipping event of the flanks of the feature suggest the reverse, as the top is soft and the base hard. Just to its right, where 'post-feature' mudstone sits on syn-rift, the basal event is less strong, implying that the feature is even less dense than the surrounding mudstone. Several posters noted that shaped features had been drilled assuming they were pinnacle reefs in various other basins in the world from New Zealand to Turkey; anecdotes that usually ended ruefully in an old volcano. This may be evidence of sampling bias because fewer carbonate reefs are discovered by accident by a well targeting an igneous volcano.

Different Form of Extrudite?

A non-mud or igneous extrudite model suggested that it could be an erosional remnant or even a prograding point bar. There were some quite detailed observations of the internal geometry of the feature; there appears faintly to be a series of internal reflectors parallel to the dipping flanks, again suggesting construction via eruption in some form from a central point. Some observers saw this as evidence of extrusion, but others did not think there was enough internal variation versus analog volcanics that they had seen, as they expected volcanics to be polyphased. The steeply dipping layers within the feature suggest a more central construction rather than an erosional remnant which could be expected to have base-parallel rather than flank-parallel internal bedding.



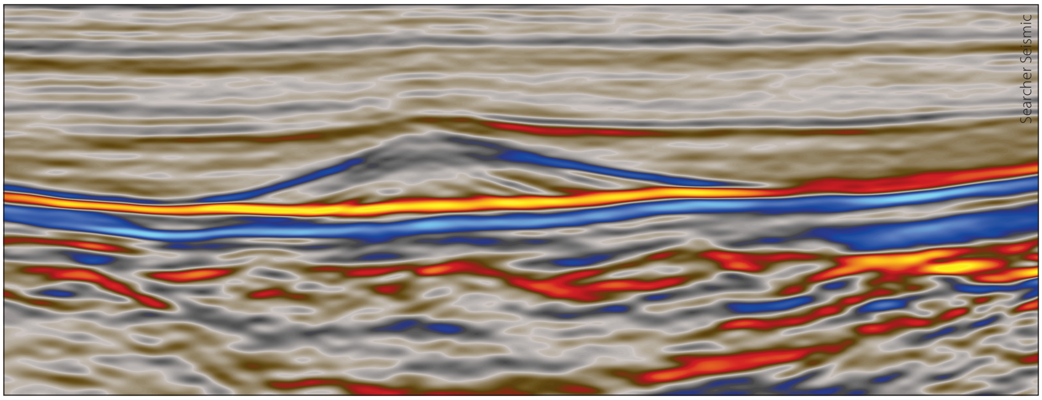
An example of a carbonate build-up seen on Searcher's seismic from Papua New Guinea.

Another non-mud or igneous extrusion suggestion was a salt diapir, yet there is no stock connecting to the halofer and not enough disruption to make a diapir a candidate. However, salt could represent the body of the feature; it is similar to a remnant salt wall between two sediment pods, as seen in other salt provinces like Gabon or the UK Central Graben. The occurrence of salt walls with sediment pods between them could explain why the structure to the left of the feature is also soft topped, although rather less perfectly formed; could it be another volcano or relict salt wall? However, salt with a soft kick top (unlikely unless deeply buried or surrounded by carbonate), in a basin where salt is not recognized and most likely has a deepwater setting does not seem likely, so we will park that in case we run out of other models.

If we rule out the carbonate, relict and salt hypotheses in favor of an extrusive, the issue for the igneous model is the soft top. Glenn Lovitz suggested that cinder cones may be soft topped with a thick tuffaceous final or major late flow that is highly porous, i.e. low velocity (see webinar Abdulkader M. Afifi, 2020). A lower impedance compared to the bland shales above could be enhanced by subsequent clay diagenesis of the felsic component. Glenn notes that mapping the internal geometry can differentiate between a pinnacle reef and an extrusive, but the nature of the extrusion, be it magma or fluidized clastics, could perhaps generate the same constructional geomorphology.

Why No Feeder Pipe?

But a bigger problem awaits all the extrusive models. Several contributors noted that the feature has no feeder pipe or disturbance below the cone, at least not visible on this section. Some great seismic examples were posted showing drilled volcanoes that had very disturbed substrate. If it were a cinder cone or mud diapir then some material, either molten lava or fluidized mud, will be supplied from depth to the then sea floor, where the feature is built. Why can we not see a conduit of material beneath it?



The feature at 'true scale'.

current erosion, mass-wasting and depositional processes, in relationship with sea-level change, acting in both subaerial and submarine environments. However, the mudstones overlying the feature are deepwater sediments, so presumably some of these processes may have had little chance to modify the geometry before the feature was buried.

Of course, absence of evidence is not evidence of absence per se. The feeders may have caused disruption below seismic resolution (especially if they were clastic injectites) or the line or feeder pipes need not have been central. Although you only get a pointed crest on a conic section if you go through the cone top, many cinder cones have pointed caldera-rim ridges that are offset from the vent center. Allan Scardina favored a volcanic cone subject to a better understanding of the paleo-bathymetry of the onlapping section; he felt a lack of feeders is not definitive evidence as they can be difficult to spot. It was exciting to see a post regarding the non-visibility of a possible feeder pipe, with an example from offshore New Zealand including different types of igneous seismic facies (Bischoff et al., 2019).

When Discover Geoscience posted the original image, they also noted the lack of obvious feeder pipes and also the aspect ratio (height to width 0.1) and the fact that the same geometry was present on the cross line, making it likely that we are looking at a conical feature, albeit rather more squashed flat than the image suggests. Several posters took the time to recreate the image in 'true scale' – a discipline that perhaps we should endorse more often as it allows our models to be informed more accurately by real-world observation. However, the aspect ratio is not uncommon in monogenetic submarine volcanoes composed of poorly consolidated tephra showing steep slopes and pointy or flat tops, often characterized by sub-vertical knolls (e.g. Cavallaro and Coltelli, 2019). Submarine extrusives are often not as delightfully pointy as this example because of the interplay between volcanic activity, wave and current erosion, mass-wasting and depositional processes, in relationship with sea-level change, acting in both subaerial and submarine environments. However, the mudstones overlying the feature are deepwater sediments, so presumably some of these processes may have had little chance to modify the geometry before the feature was buried.

The surrounding mudstones onlap the feature, do not seem to have eroded it, and appear to have compacted more than the feature itself (slightly arcuate downward on the flanks), suggesting that it is made of material that behaves differently to the depositional mudstones surrounding it; either mud in the feature is not de-watering on loading, or they comprise material that is not compacting. This fueled the reasoning that the feature comprises a hard (igneous by inference) material, more solid than the mudstones around it and perhaps not consistent with it being comprised of soft mud volcano extrusives. More solid but lower density with that soft seismic kick?

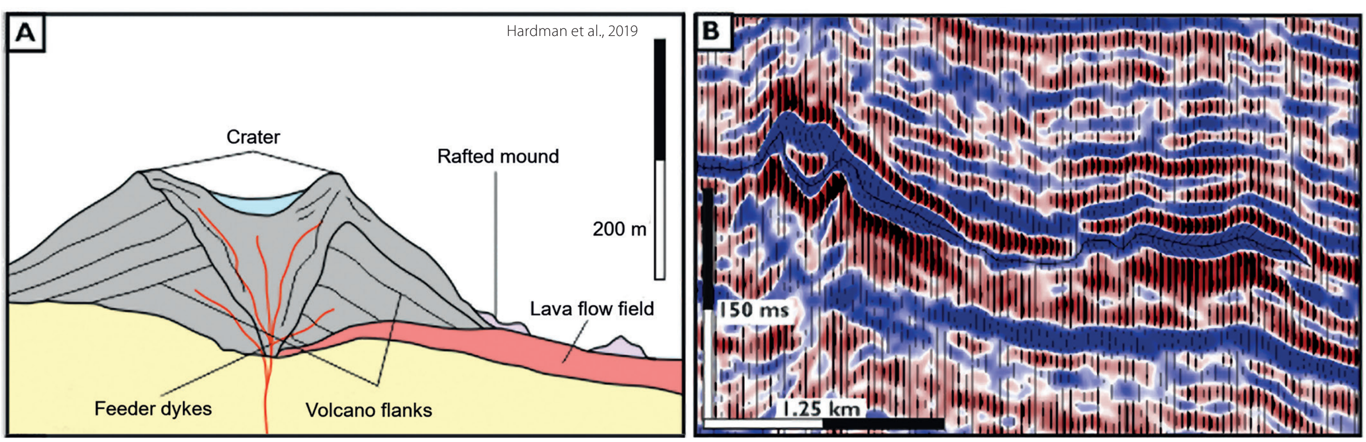
The presence or otherwise of distortion in the seismic above the crest of the feature drew attention. Some identified a gas escape distortion in the overlying strata, others unambiguously said there was no sign of gas escape, only faulting due to compaction. That fluid flow might continue through a system post-mud eruption and burial is not impossible, yet it is also not compulsory, nor probably limited only to clastics and could come from volcanics too.

Curiouser and Curiouser

So two parallel trains of argument were slugging it out in the LinkedIn feed: the volcanic cinder cone or the mud extrusive. The salt diapir, carbonate build-up and erosional remnant have all left the venue on stretchers with mild concussion.

But now comes a third boxer into the ring: Charlotta Luthje said: "I put my money on a sand volcano at that scale." This is

(A) Cross-section through a cinder cone, adapted from Németh and Kereszturi (2015). (B) Seismic line across a cinder cone and lava flow highlighting the general morphology and seismic response.



an awesome thought. Perhaps the sand was less compressible than mudstone so the compaction difference we see between the feature and the mud either side could be explained. Mads Huuse added into this line of thought by supplying an analog from the North Sea – a subsurface feature interpreted as a sand volcano (Andresen et al., 2009). He could not prove the analogy was a sand volcano – it was just an interpretation.

Hans Ladegaard pulled together a set of observations that seemed to establish this model as a firm candidate. He noted that the internal stratification suggests it is a build-up rather than an erosional remnant. The soft top and the brightening of the hard base shows that the body has lower AI than the surrounding rocks, ruling out salt, carbonate and possibly also a volcanic origin. There is some differential compaction of the surrounding strata which is difficult to reconcile with a pure mud volcano (although it could be a result of late movement), suggesting a sandy volcano, which may also explain the vague hints of fluid escape above the crest.

Well, although we have looked and cannot find any outcrops of sand volcanoes on this scale and geometry, at least our dancing around the various alternatives has generated a prospective model. Sand, sealed by shales but connected to the deep syn-rift by sand conduits for hydrocarbons to ooze up, a high net/gross sandstone target in a shape of a right cone, full of oil.

Geoscience at its Best

From a single seismic line and binary question we have had many firmly held alternative models discussed and dissected, which we have perhaps been biased enough to whittle down to the one with hydrocarbon prospectivity!

Perhaps the conclusion is that an interpretation is only as certain as the richness of the observations upon which it is based and the alternatives considered. Given a binary question in an increasingly polarized binary world, we are proud of the geoscience community for coming together and finding a third way. This is geoscience at its best.

References available online.

Cross-section through a sand volcano. County Clare, Ireland.