THE ORIGINS OF THE MAGNETIC ANOMALIES OF GOAT ROCK ON BANKS PENINSULA, NEW ZEALAND

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Abstract

Remanent magnetism is commonly found in igneous rocks. If exposed to extreme conditions or events, such as lightning, the paleomagnetic signal can be overwritten with an anomalous magnetic signal. Several magnetic anomalies, with unknown origins, have recently been discovered on Goat Rock, an exposed lava dome that lies along a ridge. Goat Rock, part of the Miocene volcanic complex that formed Banks Peninsula, New Zealand, is a local topographic high, a logical location for lightning to strike. This study accurately maps the anomalies on Goat Rock and hypothesizes why they exist and how they formed using an extensive literature review on anomalous remanent magnetism.

Introduction

Banks Peninsula, east of Christchurch, New Zealand, is comprised of several Miocene volcanic groups, the two largest volcanoes being the Lyttelton volcano to the west and the Akaroa volcano to the east. Goat Rock, shown in Figure 1, is an exposed lava dome from the Akaroa volcano, 9.0 – 8.0 Ma (Sewell 1988). The location of Goat Rock is depicted in Figure 2. The dome has been broken into two zones, Upper and Lower Goat Rock. The magnetic anomalies were discovered accidentally on a routine field mapping exercise with simple hand compasses.

Background on Magnetism

There are many ways for the remanent magnetism found in rocks to form. Magnetization that forms naturally is referred to as Natural Remanent Magnetism, or NRM. The NRM of an igneous rock consists of the primary magnetization that forms during cooling, and any signal from secondary magnetization events. In magmatic bodies, the magnetic fields of individual ferromagnetic crystals are randomized and disordered, but as they cool past the Curie point, the individual crystal fields will align themselves and the rock will acquire a Thermoremanent Magnetization, or TRM. The TRM will always be parallel to the magnetic field the rock is cooled in; there have been no observations of a TRM oblique to the parent magnetic field (Cox 1961). It is also theoretically possible for the magnetism in a rock to be anti-parallel to the field in which it formed, but this is highly unlikely to occur, and has yet to be seen (Cox 1961). Because the magnetic field of the Earth is much stronger than any field that could form within the molten rock from random crystal field orientations above the Curie point, the orientation of the TRM is tightly confined and will vary less than a few degrees across the entire rock. The TRM of an igneous body is very useful for paleomagnetism research, as it is very difficult to destroy. New magnetic signals may overprint the TRM, but they can be removed using various laboratory techniques to reveal the original signal (Cox 1961).

Secondary magnetism events can cover a wide range. The events can range in strength and duration from seconds to eons, and the magnetic signal preserved will reflect these conditions. The most common form of secondary magnetism is called Viscous Remanent Magnetism, VRM, which is continuously changing and is in virtually every rock. VRM slowly builds up as a rock is exposed for an extended period of time to a weak magnetic field. The VRM will be aligned with the Earth's current magnetic field, and the strength of the VRM is logarithmically proportional to the time the rock has been exposed to the field (Butler 1992). Because VRM affects the entire rock as a whole and the signal remains relatively weak in comparison to the TRM, it is not generally considered an anomaly and can be thought of simply as noise in paleomagnetic data.

Anomalous Remanent Magnetism, ARM, refers to anything diverging from the overall magnetism of the primary TRM in an igneous rock. An ARM could have many possible causes, even including mechanical processes during the primary magnetization, such as crystals with a high Curie point forming and acquiring a specific TRM then being moved within the magma chamber or lava flow below their Curie Temperature (Cox 1961). This formation hypothesis is highly unlikely and the majority of ARM signals will form post solidification. Some ARM can be caused by biological factors, either by anthropogenic or bacterial sources. Certain types of bacteria contain intracellular magnetite, used for navigation, which can be deposited after death (Dunlop & Özdemir 1997). Anthropogenic sources can include fires, ovens, and kilns; if the fire becomes hot enough to pass the Curie temperature, it can cause TRM to form (Maki 2005). These anomalies will be locally contained within the site of the oven.

Another type of secondary magnetization is Chemical Remanent Magnetization, CRM. In this case the magnetization forms when the mineralogy of the area changes. It involves either chemical reactions that form ferromagnetic minerals from the existing rock, or the precipitation of ferromagnetic minerals (Butler 1992). This type of magnetization is more prominent in sedimentary rocks.

Isothermal Remanent Magnetization, IRM, occurs when a substance is subject to very strong magnetic fields for a short period of time, at a constant temperature. These events last at most a few minutes (Dunlop & Özdemir 1997). IRMs can have very strong signals, but the longevity of an IRM is fickle; exposure to a magnetic field stronger than the field that formed the IRM can erase all evidence of its existence. This characteristic has proven useful for standard paleomagnetic surveys, as it can be removed in the lab to reveal primary magnetization. A common anthropogenic cause of IRM is drilling. The rotating steel barrel of a coring device can become magnetized and in turn magnetize the sample. Drill-induced Remanent Magnetization, DIRM, intensity can increase from the core center to the core wall by a factor of ten (Dunlop & Özdemir 1997). Because the Goat Rock area has not been subject to previous study, this magnetization event can be ruled out immediately.

The most frequent natural cause of an IRM is lightning discharge, referred to as Lightning Induced Remanent Magnetism, LIRM. LIRM have been recorded in sediments as well as solid rock and manmade materials, such as brick or concrete (Maki 2005). The signal of LIRM is very intense and can form dendritic, radial or linear patterns (Jones and Maki 2005). The high temperature of a lightning strike can melt carbonates and silicates and can even cause metals to melt out silicate rocks. This could create distorted mineral lattice and sometimes microfeatures of pure metal sheets (Mahaney and Krinsley 2012). In soft sediment, fulgurites, tubes of fused sand, can be found. Thin layers of glass on the surface of metamorphic rocks have been found along lightning strike marks by Appel et al 2006. In addition, the lichen along the strike trace was burnt off.

Methods

The Anomalous Renament Magnetism, ARM, on Goat Rock was mapped on foot, using an orienteering hand compass and aerial photographs. This method is rather rudimentary, and because of this, only intense anomalies were mapped. After completion of mapping, the area was analyzed for trends concerning the relative location, size, magnetic intensity and dispersal of ARM zones, as well as analysis comparing the distribution of ARM with regard to the structure of the underlying rock itself.

Samples of Goat Rock have also been taken from magnetically neutral zones in addition to ARM zones. The samples have undergone oriented thin section analysis to determine if areas containing ARMs have a preferential ferromagnetic mineralogy or alignment when compared to neutral areas of Goat Rock.

An extensive literature review on the subject of anomalous remanent magnetism was compiled after completion of the mapping and analysis to avoid introduction of sampling bias. The different ARM forming events were compared to the data collected from the Goat Rock ARM, and deemed probable or improbable sources for the magnetic alterations observed.

Storm data from Banks Peninsula were collected from New Zealand's National Climate Database from NIWA. This includes data from the two closest climate weather stations to Goat Rock: Onawe Duvauchelle Bay Station and Akaroa Rue Lavaud Station, 9.1km and 11.8km from Goat Rock respectively. Analysis attempted to discern the probability of lightning discharge striking Goat Rock.

Results

There are two major regions of Goat Rock: Lower Goat Rock to the east and Upper Goat Rock to the west. Upper Goat Rock is akin to a peninsula of rock, with steep cliffs on all sides but the steeply ramping northeast. Lower Goat Rock has less elevation change, gently inclining towards a drop-off on the southeast side that turns and continues partially up a small low-lying section between the two areas. Magnetic anomalies were found in both regions; their locations are illustrated in Figure 3. ARM clusters of 180° pole reversals were found on the southwest cliff of Lower Goat Rock and around the edge of the middle valley. The locations of the clusters trended in a general east – west direction across Lower Goat Rock. Within individual clusters, different patterns were seen and some areas contained larger ARM sites than others.

The lower flank of Upper Goat Rock was covered in loose boulders, but half way up, an in situ rock was found with ARM. Two more ARM sites were found, and a rock sample was acquired, on the way to the summit. The top of Goat Rock was highly affected by remament magnetism, in both intensity and area. The largest area of affected rock spread out over 10 meters along the ridge, and the height of affected compass measurements was undeterminable, but at least 1.5 meters. There were a few other areas along the top of the rock with very large ARM. Upper Goat Rock ARM sites were much larger and stronger that the Lower Goat Rock ARM sites. Complete descriptions of each anomaly site are listed in Table 1.

Figure 4 depicts the lightning strike frequency of New Zealand (Brenstrum 2004). Banks Peninsula has a frequency of less than 0.05 lightning strikes per kilometer per year, which is a probability of one lightning strike in 20 years. The weather data collected from NIWA is shown in Figure 5. The Onawe site was active from 1955 to 1972, and the Akaroa site was active from 1977 until 2001. The analysis shows that thunderstorms can happen in any month but the higher storm frequency is during the summer.

Discussion

The small Goat Rock Anomalous Remanent Magnetism sites all appear to run in ribbons. These ribbons trend east – west. The anomalies are strong enough to register with a standard hand compass when the ARM alignment deviates from true north. The larger Goat Rock ARM sites are very chaotic and sometimes over 10 meters in length. A compass reading in the vicinity could be altered over 2 meters above an outcrop. There are no apparent visual differences, even in thin section, between the rocks with ARM and surrounding rock. The most common ARM sources are listed below and compared to Goat Rock ARM characteristics.

Intrusive body

According to Jones and Maki 2005, magnetism from lightning is often incorrectly interpreted as intrusions. This process could cause ARM if the rock was formed in stages, with certain areas solidifying at different times and thus with a different TRM. The Goat Rock lava dome is thought to have formed in one stage, which negates this idea. There is also no evidence of any sort of secondary dyke or sill.

Chemical Remanent Magnetization

The process of creating ARM through CRM takes a long time and is completed through digenesis. Iron-bearing minerals are slowly replaced by hematite crystals (Larson et. al 1982). The thin sections of a Goat Rock anomaly showed almost no alteration, Figure 6, which means chemical remanent magnetization is not the source. In addition, if CRM were the cause of the ARM, it would logically have affected the entire area more evenly as Goat Rock weathered.

Anthropogenic Source

The anomalies associated with prehistoric ovens and kilns are not very strong and tend to be small, 1.5m in diameter (Maki 2005), and are locally contained within the site of the oven. These are commonly found with other artifacts denoting the presence of hominoids and/or a fire, such as pottery shards, charcoal or fire rings, none of which were found on Goat Rock. Prehistoric ovens are also more often found carved in soils than bedrock. Given the strength and enormity of the Goat Rock ARM, anthropogenic sources may be ruled out.

Lightning

Beard et. al. (2009) have mapped out several LIRM features using a high resolution magnetosurvey. Their discoveries suggest that the typical pattern of LIRM resembles a "starfish", where each arm has a positive and a negative side. The width of a radial arm is often 2 to 5 meters but the entire LIRM itself can be up to 25m. This pattern is shown in Figure 7. Because the mapping done in this paper was completed using very basic equipment, the magnetic signals recorded will not resemble the starfish patter. LIRM features are bipolar, and the polarity is always perpendicular to the long axis of the feature (Jones and Maki 2005). This was seen on Lower Goat Rock, with the east-west trending anomalies that were reverse-polarized. The anomalies of Upper Goat Rock were very convoluted and ranged from 30° to 180° deflections from true north. This could be the manifestation of the central part of the LIRM, where the different arms are meeting up and the polarity would switch over small distances. There was even one place were the border between the two sides of a feature was found, Figure 8. The mirco-features associated with LIRM, glass and distorted minerals, were not found on Goat Rock, but could have easily been eroded (Maki 2005). Though fragile features may get broken down, the LIRM can remain for long periods of time. Shimizu et al. (2007) have been studying a magnetic anomaly from a lightning strike since 1982, and the magnetic intensity of the area has remained the same.

The weather data that has been collected from Banks shows that lightning storms are possible in the area, though the lightning strike frequency is not very high. The LIRM of the area are probably relatively old, based on the lack of more delicate lightning related features, such as glass, and the regrowth of lichen. The Lower Goat Rock Anomalies probably belong to one strike, but the anomalies of Upper Goat Rock were born of multiple strikes, based on the distances they cover.

Conclusion

Based on the review of previous studies of magnetism, and detailed field observations, the source of the Goat Rock magnetic anomalies is almost certainly lightning. The exact positions of the lightning strikes are yet undetermined, but with future study using more technical equipment they could easily be found. The polarity and intensity of the lightning strikes could also be determined with a more technologically advanced study (Sakai and Yonezawa 2002; Beard et. al 2009; Verrier and Rochette 2009). With proper equiptment, future studies could officially classify the anomalies as LIRM, using guidelines from Dunlop et al. (1984). Though lightning strikes in Banks Peninsula are uncommon, they do occur in high elevations, and their effects are preserved in remanent magnetism.

References

Appel, P. W. U., Abrahamsen, N., Rasmussen, T. M. (2006). Unusual Features Caused by Lightning Impact in West Greenland. *Cambridge University Press* 143 (5), 737–741.

Beard, L. P., Norton, J., Sheehan, J. R. (2009). Lightning-Induced Remanent Magnetic Anomalies in Low-Altitude Aeromagnetic Data. *Journal of Environmental & Engineering Geophysics* 14(4),155-161.

Brenstrum, E. (2004). Weather. *New Zealand Geographic* 70, 4–6

Butler, R. F. (1992) "Origins of Natural Remanent Magnetism." *Paleomagnetism: Magnetic Domains to Geologic Terranes*. Boston: Blackwell Scientific Publications, 32-62.

Cox, A. (1961) Anomalous Remanent Magnetization of Basalt, *U.S. Geologic Survey Bulletin, v*. 1083–E, 131–160.

Curie point. (2012). In Encyclopædia Britannica. Retrieved from http://www.britannica.com/EBchecked/topic/146902/Curie-point

Dunlop, D. J., Özdemir, Ö. (1997). *Rock Magnetism: Fundamentals and Frontiers*. Cambridge Univ. Press.

Dunlop, D J., Schutt, L.D., & Hale, C.J. (1984). Paleomagnetism of Archean rocks from northwestern Ontario: III. Rock magnetism of the Shelley Lake granite, Quetico Subprovince. *Canadian Journal of Earth Science*, 21, 879–886.

Jones, G., Maki, D. L. (2005). Lightning-Induced Magnetic Anomalies on Archaeological Sites. *Archaeological Prospectection* 12, 191–197.

Larson, E. E., T. R. Walker, P. E. Patterson, R. P. Hoblitt, J. G. Rosenbaum (1982), Paleomagnetism of the Moenkopi Formation, Colorado Plateau: Basis for Long-term Model of Acquisition of Chemical Remanent Magnetism in Red Beds, *Journal of Geophysical Research*, 87(B2), 1081–1106.

Mahaney, W.C., Krinsley, D. (2012). Extreme Heating Events and Effects in the Natural Environment: Implications for Environmental Geomorphology. *Geomorphology* 139–140, 348–359.

Maki, D. (2005). Lightning Strikes and Prehistoric Ovens: Determining the Source of Magnetic Anomalies Using Techniques of Environmental Magnetism. *Geoarchaeology: An International Journal Vol. 20, No. 5,* 449–459

Sakai, H., Yonezawa, K. (2002) Remanent Magnetization as a Fossil of Lightning Current. *Proceedings of the Japan Academy*, 78, Ser. B.

Sakai, H., Sunada, S., Sakurano, H. (1998), Study of Lightning Current by Remanent Magnetization. *Electrical Engineering in Japan*, 123: 41–47

Shimizu, H., Koyama, T., Koyama, S., Utada, H. (2007). A Geomagnetic Total Intensity Anomaly Originated from Lightning-Induced Isothermal Remanent Magnetization: Case of the Yatsugatake Magnetic Observatory, Central Japan. *Earth Planets Space*, 59, 141–149.

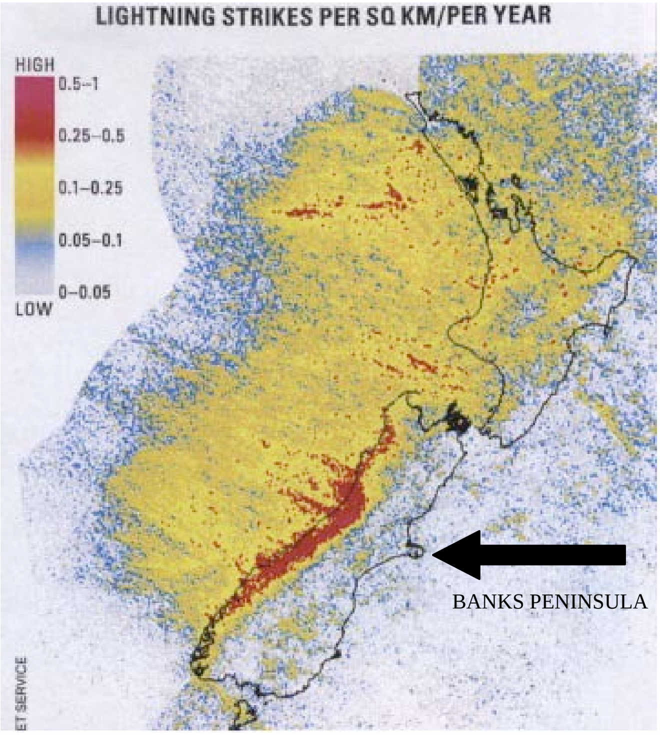
Sewell, R. J. (1988). Late Miocene Volcanic Stratigraphy of Central Banks Peninsula, Canterbury, New Zealand. *New Zealand Journal of Geology and Geophysics Vol.* 31, 41-64.

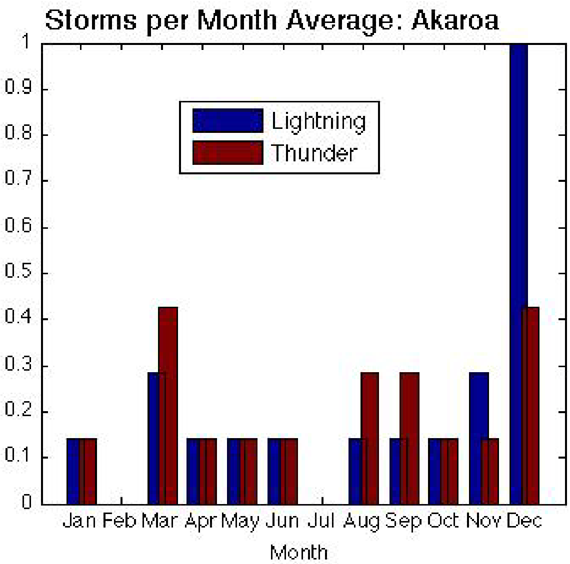
Verrier, V., Rochette, P. (2002). Estimating Peak Currents at Ground Lightning Impacts Using Remanent Magnetization. *Geophysical Research Letters*, 29: 18, 14-1

Table 1:

Site	Complete Reversals	Distribution Pattern	Notes
1	1	N/A	First in situ magnetism along south cliff
2	8	Line trending due east	Spread over 5 meters. 90° bearing to stop 1
3	3	Aligned vertically	One reversal is 11cm tall zone. 95° Bearing to stop 2
4	1	Zone of Anomalous Magnetism	Area ~4 meters. Magnetic deflection ranges from 20° to 40° for majority of anomaly. 90° to stop 2
5	0	N/A	Only 40° deflection. 90° bearing to stop 4.
6	8	Inclined Plane	~1.5m spread, trending east-west, dip following cliff face, ~45°. 98° bearing to stop 2.
7	5	Line	Trending 95°.
8	4	Line	~1 meter spread. 62° from stop 4 and 7
9	3	Line / Tear Drop	One 110cm by 51cm large teardrop shaped reversal, trending 114° along axis. Whole outcrop is affected with, ~20°- 40° deflection.
10	N/A	Whole Outcrop	Whole outcrop is between 130°-180° deflection.
Summit	N/A	Whole Outcrop	Entire summit is affected, over 2 meters high. Deflection is from 40° to at least 90°


Banks Peninsula
Goat Rock
Lower
Upper
New Zealand
5 4
3
2
1
6
7
8
9
N


LIGHTNING STRIKES PER SQ KM/PER YEAR
HIGH
0.5–1
0.25–0.5
0.1–0.25
0.05–0.1
0–0.05
LOW
BANKS PENINSULA


Storms per Month Average: Akaroa
Lightning
Thunder
0
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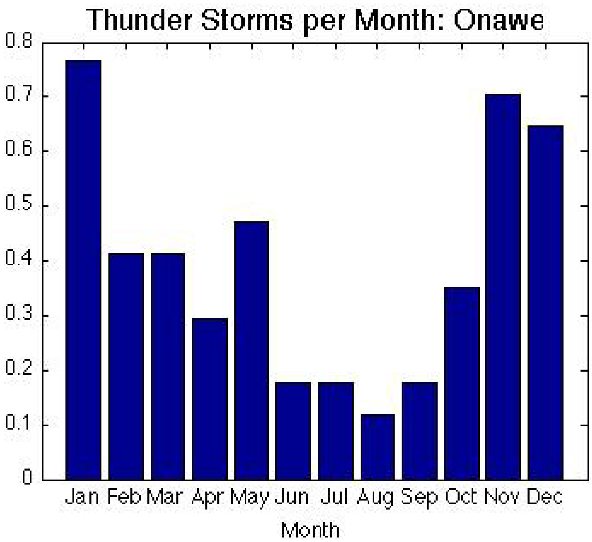
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
Month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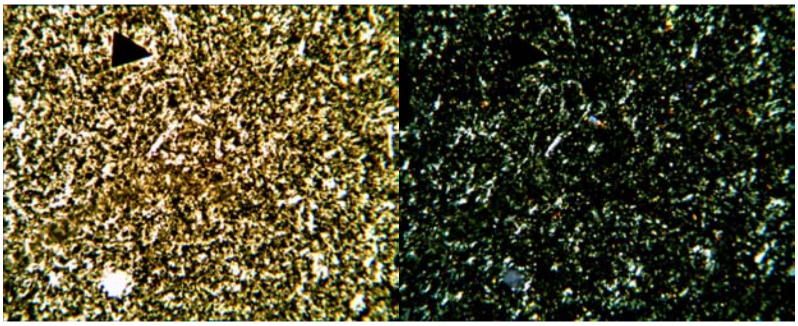

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Figure 1:

The Goat Rock study area. Viewed from the west. Goat Rock is a local topographic high.

Figure 2:

Study area map: Goat Rock's location on Banks Peninsula, New Zealand. Upper Goat Rock is higher topographically than Lower Goat Rock.

Figure 3:

Location of ARM. Lower Goat Rock ARMs are aligned east-west. The summit of Upper Goat Rock was comprised of large ARM areas with very strong, convoluted magnetism, denoted by the green patches. Red spots indicate at least one 180° anomaly, with respect present north. Thin section samples were taken from stop 8.

Figure 4:

Map of lightning strike density. Frequency on Banks Peninsula is < 0.05 strikes per km per year. Adapted from Brenstrum 2004.

Figure 5:

Average storm frequency recorded at two weather stations on Banks Peninsula. Storms are more frequent in the summer months than winter. The Onawe station did not record lightning.

Figure 6:

Thin section of anomaly on Goat Rock, in normal and cross-polarized light. Very little alteration has taken place to the ground mass of the sample.

Figure 7:

The "Starfish Pattern" of a lightning strike found in a high resolution magnetic survey. The anomalies are linear features radiating from a common center. Adapted from Beard et. al 2009.

Figure 8:

The two compasses point in opposite directions, showing the bipolar components of the LIRM on Goat Rock