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The Physics Underlying Gutenberg-Richter in the Earth and in the Moon

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ABSTRACT: The linear Gutenberg-Richter relationship is well-established. In any region of the Earth, the logarithm of the number of earthquakes, greater than any magnitude, is proportional to magnitude. This means that the underlying physics is non-linear and not purely elastic. This non-linear physics has not been resolved. Here we suggest that a new understanding of fluid-rock deformation provides the physics underlying Gutenberg-Richter: where the fluid-saturated microcracks in almost all in situ rocks are so closely-spaced that they verge on failure and fracture, and hence are critical-systems which impose fundamentally-new properties on conventional sub-critical geophysics. The observation of linear Gutenberg-Richter relationship in moonquakes suggests that residual fluids exist at depth in the Moon.
KEY WORDS: critical-system, Gutenberg-Richter relationship, New Geophysics, residual fluid in moonquake, shear-wave splitting, shear-wave time-delay.

0 INTRODUCTION

Distributions of earthquakes in any region of the Earth typically satisfy the Gutenberg and Richter (1956) relationship (GR)

$$\mathrm{Log}_{10}[N(>M)]=a-bM \tag{1}$$

where N is the cumulative number of earthquakes greater than magnitude M; a is a measure of the level of seismicity; and b is typically close to 1 (Richter, 1958). The value of b is the gradient of GR, where higher b indicates a larger proportion of small earthquakes, and lower b a smaller proportion of small earthquakes. Since M is proportional to the logarithm of energy, GR is a power law and approximately linear. Thus, GR demonstrates that, perhaps not surprisingly, earthquake physics is not purely elastic.

Originally specified (with remarkable insight ~60 years ago) as an empirical magnitude-frequency relationship, GR is now recognised as belonging to a huge range of natural phenomena that have been variously described (in geosciences) as displaying: self-organised criticality (Bak, 1996; Bak and Tang, 1989); fractal scaling (Turcotte, 1992; Main et al., 1990); statistical physics (Rundle et al., 2003); critical-point theory (Chen et al., 2006); and critical-systems (Crampin and Gao, 2013); amongst others. "It is one of the universal miracles of nature that huge assemblages of particles subject only to the blind forces of nature, are nevertheless capable of organising themselves into patterns of cooperative activity" (Davies, 1989).

Such critical phenomena impose a range of fundamentally-new critical properties on conventional sub-critical geophysics some of which are listed in Table 1 (after Crampin and Gao, 2013). These remarkable properties are part of a fundamental revision of many ideas in physics (and geophysics) (Davies, 1989) where familiar concepts in conventional sub-critical physics are no longer wholly valid and need to be revised. Davies (1989) calls these phenomena a New Physics, hence we suggest a New Geophysics (reviewed by Crampin and Gao, 2013).

The linearity of GR has been known for over half a century, but the physical phenomena underlying GR has not been resolved. Here, we show that critical-systems provide a New Geophysics for GR that has implications for a wide range of geoscience applications. Section 3 is a brief summary of New Geophysics. Seven of the eight new properties in Table 1 have been observed, in some cases, a huge number of times. The exception, P6, Controllability, has not yet been tested.

1 THE CONUNDRUM

The puzzle, the conundrum for geoscience, is that conventional linear purely-elastic geophysics has satisfied tens of thousands of theoretical, analytical, and observational investigations of earthquakes and seismic-wave propagation in the Earth, despite GR demonstrating that non-linear elasticity controls fundamental aspects of geophysical behaviour. GR clearly demonstrates non-linear elasticity and shows that the behaviour of seismic waves in the Earth is incompatible with conventional linear purely-elastic sub-critical geophysics. What has been lacking previously is an understanding of the physical

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Table 1 Properties of the New Geophysics of critically-microcracked rock [1]

	Property	Effects
P1	Self-similarity	Logarithmic plots of many properties are linear [1, 2]
P2	Monitorability	Behaviour can be monitored with shear-wave splitting [1, 3]
P3	Uniformity	Statistical behaviour is more like other critical-systems than it is to the underlying sub-critical geophysics [1, 3]
P4	Calculability	Behaviour is more uniform than sub-critical geophysics, and can be modelled or calculated with the equations of anisotropic poro-elasticity (APE) [1, 3, 4, 5, 6, 7]
P5	Predictability	If impending changes can be quantified, behaviour can be predicted [1, 7]
P6	Controllability	If conditions can be monitored (P2), calculated (P4), and modified by injection pressures, say (P5), then in principle the behaviour of the in situ rock mass can be controlled by feedback (optimising flow-directions by fluid-injection, say, in hydrocarbon production)
P7	Universality	Effects pervade all available space: upper- and lower-crust, upper mantle [1, 8, 9]
P8	Sensitivity	Butterfly's-wing-effect sensitivity to miniscule differences in initial conditions [5, 8, 9, 10]

[1] Crampin and Gao (2013); [2] Gutenberg and Richter (1956); [3] Crampin and Zatsepin (1997); [4] Crampin (1999); [5] Crampin et al. (2002); [6] Crampin et al. (2004b); [7] Angerer et al. (2002); [8] Volti and Crampin (2003); [9] Crampin and Gao (2012); [10] Lorenz (1972).

phenomena underlying GR. In this paper, the GR conundrum is resolved as the effects of the New Geophysics of a critically-microcracked fluid-saturated Earth.

One exception to purely-elastic behaviour in conventional sub-critical geophysics is anomalous attenuation which is usually attributed to some form of scattering and/or visco-elasticity. It is thought that anomalous attenuation due to viscoelasticity, say, would cause only second-order effects, and is not thought to be directly related to GR. New Geophysics, which is dependent on the mere presence of fluid, not its properties, and viscoelasticity will be neglected in this discussion.

The full implications of the linearity of GR are not generally recognised. Perhaps surprisingly, the interpretation of GR is usually limited to the conclusion that the linearity, the self-similarity, implies that any small earthquake has some probability of 'cascading' into a larger event (Geller, 1997; Geller et al., 1997; Turcotte, 1992). Whether any particular small earthquake cascades into a larger earthquake depends on miniscule details of the initial conditions. This means that earthquakes cannot be predicted in a deterministic sense. However accurately the behaviour of an earthquake source is matched by a particular geophysical model, the match is unrepeatable because initial (unknowable) conditions can never be repeated in sufficient detail to replicate the calculations. Consequently, it has been assumed that only probabilistic prediction is possible (Geller, 1997; Geller et al., 1997).

What is typically neglected in this argument is the recognition that the linearity of GR, the self-similarity, is the key property that demonstrates that the behaviour of almost all in situ rock is critical. Phenomena that are critical-systems have properties that are fundamentally-different from conventional sub-critical geophysics (Crampin and Gao, 2013; Davies, 1989). The properties in Table 1 are so different from those of conventional sub-critical geophysics that the claim to a New Geophysics appears justified.

Note that GR earthquake distributions cascading into larger events is physically implausible. Larger earthquakes can only occur if sufficient stress-energy has accumulated to be released by the appropriate magnitude event. Without sufficient stress-accumulation, 'cascading' is impossible. Such stress-accumulation can be monitored by SWS (Crampin and Gao, 2013).

2 A BRIEF SUMMARY OF NEW GEOPHYSICS

Analysis of worldwide observations of stress-aligned SWS throughout the Earth's crust and upper mantle shows that distributions of fluid-saturated stress-aligned vertical microcracks are so closely spaced that they verge on fracture-criticality and fracturing if there is any disturbance (Crampin and Peacock, 2008, 2005; Crampin, 1994). In the uppermost ~400 km of the mantle, where SWS is observed (Savage, 1999), the 'microcracks' are expected to be intergranular films of hydrated melt (Crampin, 2003). Phenomena verging on failure in this way at singularities (aka bifurcations, double-points, tipping-points, or in the Earth, fracture-criticality) are critical-systems which are part of a New Physics (Davies, 1989), hence the proposed New Geophysics reviewed by Crampin and Gao (2013). Critical-systems occur in all complex heterogeneous interactive phenomena as they approach singularities (in the case of the Earth, the singularity is at fracture-criticality), where below criticality the behaviour can be calculated/modelled by standard conventional sub-critical physics (or geophysics). However, at singularities there is deterministic chaos, where the behaviour can still be calculated, but the results may show orders of magnitude differences for miniscule differences in the initial conditions (Lorenz, 1972). Such critical-systems of complex heterogeneous interactive phenomena are common: the weather; climate change; the life cycle of fruit flies; stellar radiation; the New York stock exchange; etc. (Crampin, 2003). Hence, it must be expected that the Earth, an archetypal complex heterogeneous interactive phenomenon, must also be a critical-system with Lorenz-type sensitivity to initial conditions. The criticality of New Geophysics imposes a range of fundamentally-new properties on conventional sub-critical geophysics, some of which are listed in Table 1 (Crampin and Gao, 2013). All properties in Table 1 have been observed (with one exception), in some cases many times. The exception, P6, Controllability, has not yet been tested. These properties cannot be understood by geoscientists restricted to experience in conventional sub-critical geophysics. A paradigm shift in understanding required.

Evidence supporting New Geophysics are the 19 different phenomena along millions of individual source-to-geophone ray paths (listed in Table 2 of Crampin and Gao, 2013) and the four questions/conundrums about various aspects of geophysics, that cannot be explained by conventional sub-critical geophysics (Crampin et al., 2013). This is a very substantial body of evidence that is difficult to refute.

Note that one cannot expect to understand the New Geophysics of critically-microcracked rock in terms of previous experience based only on conventional sub-critical geophysics. A paradigm-shift in understanding is required. Some geoscientists are unwilling to make this conceptual leap (Crampin, 2012), and New Geophysics remains controversial (Crampin and Gao, 2013).

3 REASONS FOR CONTROVERSY

One of the principal reasons for controversy is the general unfamiliarity with shear-wave propagation and SWS. In both earthquake and hydrocarbon seismology, the vast majority of current seismic observations and analyses are of P-wave propagation. Because of high acquisition costs and analysis complexity, investigations of shear waves and SWS are typically neglected. Consequently, since liquid-saturated microcracks are almost transparent to P-waves (Crampin, 1993), New Geophysics, whose principal diagnostics are the behaviour of shear-waves and SWS, is almost invisible to most current seismic observations, and New Geophysics remains controversial.

Although earthquakes cannot be deterministically predicted (Geller, 1997; Geller et al., 1997), the properties of New Geophysics allow earthquakes to be stress-forecast, where we use the term ‘stress-forecast’ rather than ‘predict’ or ‘forecast’ to emphasise the different methodology (Crampin et al., 2008, 2004a, 1999). Stress-accumulation and the following stress-relaxation, as microcracks coalesce onto the impending fault-plane, has been monitored by analysing SWS above swarms of small earthquakes (Crampin and Gao, 2013; Crampin et al., 2008, 2004a, 1999; Gao and Crampin, 2008, 2004) sometimes at substantial distances from the impending epicentre (Variations in SWS were observed in Iceland before the 2004 M_w 9.2 Sumatra Earthquake at ~10 500 km from Indonesia, Crampin and Gao, 2012). Observations of SWS potentially allow the time, magnitude and, in some circumstances fault break, of impending earthquakes to be stress-forecast (Crampin and Gao, 2013).

Note that observations of SWS do not measure or forecast stress. Observations of changes in SWS monitor in the effects of changes of stress on the geometry of distributions of fluid-saturated stress-aligned microcracks.

4 SHEAR-WAVE SPLITTING (SWS)

It is sometimes argued that since SWS is a minor second-order feature of shear-wave propagation, how can it be so important? We contend that it is New Geophysics not SWS that is important. SWS is the principal diagnostic for monitoring, calculating, and formulating the microcrack deformation of New Geophysics, where the properties in Table 1 affect or influence almost all aspects of the theory, observation, and exploitation of solid Earth geophysics.

New Geophysics is not caused by SWS. SWS is merely the seismic phenomenon that allows the effects of stress on the geometry microcrack distributions to be measured and quantified. Understanding the implications of changes in SWS leads to a fundamental revision of our understanding of fluid/rock deformation (Crampin and Gao, 2013) in virtually all solid earth geoscience in the crust and above the 400 km discontinuity in the mantle where SWS in mantle phases is observed (Savage, 1999).

5 DISCUSSION OF THE GUTENBERG-RICHTER RELATIONSHIP IN EARTHQUAKES

The physics underlying the Gutenberg-Richter relationship in the Earth is the stress-induced manipulation of the geometry of the ubiquitous distributions of compliant stress-aligned fluid-saturated crack-critical microcracks pervading almost all rocks throughout the crust and uppermost mantle. SWS indicates that these ‘microcracks’ are so closely-spaced that they verge on fracturing, and hence are critical-systems (Crampin and Gao, 2013; Crampin and Peacock, 2008, 2005; Crampin, 1994; Davies, 1989).

Known as the New Geophysics (Crampin, 2006), critical-systems impose a range of fundamentally-new properties on conventional sub-critical geophysics including the linearity of GR (Crampin and Gao, 2013). These properties have implications for a wide range of geophysical investigations, including hydrocarbon production, CO_2-sequestration, burial of nuclear-waste, slope stability, earthquake stress-forecasting, and many more. We suggest New Geophysics is a fundamental advance in understanding and exploiting fluid-rock deformation in the Earth with important implications and applications in geoscience (Crampin and Gao, 2013).

Stress-induced deformation of fluid-saturated microcracks is driven by fluid movement in flow or dispersion between neighbouring microcracks at different orientations to the stress-field by anisotropic poro-elasticity (APE) (Crampin and Zatsepin, 1997). This typically leads to parallel microcracks aligned perpendicular to the direction of minimum compressional stress where, once below weathering and stress-release phenomena in the uppermost few hundred metres of the crust, the minimum stress is horizontal leading to vertical microcracks aligned parallel to the direction of maximum horizontal stress as is observed in SWS throughout the crust and upper mantle. The only anisotropic symmetry with such parallel shear-wave polarisations is transverse isotropy with a horizontal axis of symmetry (Crampin and Kirkwood, 1981), or a minor variation thereof (Crampin and Gao, 2013; Crampin and Peacock, 2008, 2005).

APE deformation is driven by fluid pressures, hence GR is one of the manifestations of stress-aligned fluid-saturated microcracks in the Earth. However, GR is also observed in moonquakes in the at one time supposedly-dry lunar rocks at various depths in the deep interior of the Moon. Such linear GR in the Moon is interpreted below as direct indicators of minimal residual fluids at depth within the Moon.

6 THE GUTENBERG-RICHTER RELATIONSHIP IN MOONQUAKES

The four-station Apollo Lunar Seismic Network 1969 to 1977 recorded seismograms of lunar events showing strongly oscillatory waveforms sometimes lasting many tens of minutes or hours, typically without impulsive P- and S-arrivals. These lunar seismograms are fundamentally different from terrestrial seismograms and cannot be analysed by conventional earthquake techniques (Nakamura et al., 1982; Lammlein et al., 1974). Consequently, analysis of moonquakes still evolves, and their mechanisms, causes, and locations are not wholly finalised. Clearly, the nature of lunar seismograms is dominated by the effects of lunar structure on propagation rather than the nature of the source event.

Four types of natural seismic event have been recognised. The most numerous are the many thousands of very small thermal moonquakes, local to each seismic station, attributed to the thermal interactions of heavily fractured rocks within a few cm of the surface (Duennebier and Sutton, 1974).

The next most numerous (averaging a thousand a year) are deep moonquakes (DMQs), M<2 (Richter magnitude equivalent), on a very wide band running from WSW to NE on the nearside of the Moon. These DMQs appear to be of tidal origin and are mostly in some 250 repeated hypocentral 'nests' of events, probably 700 to 1 200 km deep (Nakamura, 2005, 2003; Nakamura et al., 1982).

There were also 28 'shallow' moonquakes in the eight-year observational period. These were high-frequency teleseismic (HFT) events, probably 100 to 400 km deep in the Moon's upper mantle, which are larger, up to M 4.8 (Nakamura, 1980) (M 5.5, Oberst, 1987). It was noticed that 23 of these events occurred during one-half of the sidereal month when the seismic network on the Moon's near side faced a particular direction in the celestial sphere (Frohlich and Nakamura, 2006). The cause of these events is speculative.

The detailed causes, mechanisms, and depths of the first three classes of lunar events are not finally established. The fourth class of event records, meteoroid impacts, is well established (Oberst and Nakamura, 1991; Duennebier et al., 1975).

The magnitudes of deep and shallow moonquakes, and meteoroid impacts each display a near-linear GR relationships with b-values of 1.78, 0.55, and 1.3, respectively (Nakamura, 1980; Lammlein et al., 1974), where, similar to Equation (1)

$$\log_{10}(N)=a-b\log_{10}(A) \tag{2}$$

N is the number of events; a is a measure of seismicity; and A is the amplitude of the seismic signal. All three lunar b-values are outside the values $0.8<b<1.2$ typically found for earthquakes, which are usually close to b=1.

The examination of lunar volcanic glasses (Saal et al., 2008) suggests that "the presence of water must be considered" in all lunar models. Lammlein et al. (1974) speculate on partial melt and pore-fluids for the deeper events. We argue above that rupture in the Earth is the result of stress-induced manipulation of fluid-saturated microcrack geometry. Stresses derived from APE microcrack interaction increase pore-pressures until the pressure on the fault-plane reach critical values at fracture-criticality and the fracture/earthquakes occur (Crampin et al., 2004b, 2002, 1999). Without fluid-saturated cracks, there is no known mechanism for fractures to reach fracture-criticality and slip to occur at depth in highly-pressurised rocks.

This suggests that GR in deep moonquakes is a strong indication that small quantities of interstitial fluids exist deep within the Moon. Intermittent 'patches' of residual interstitial fluids at depth within the moon also account for the sporadic repeated nests of DMQs. Crampin et al. (2004b, 2002) show that critically-high pore-fluid pressures, generated by APE-deformation of microcracks filled with initially normally-pressurised pore-fluids, are necessary for triggering earthquakes at depth within the Earth. We suggest that similar high pore-fluid pressures are also necessary for triggering moonquakes, where the high pressures are the response of stress acting on 'patches' of residual fluid-saturated microcracks deep within Moon.

Note that water in lunar rocks is now under vigorous investigation. The recent 45th Lunar and Planetary Science Conference 2014 had many tens of presentations on various aspects water in lunar rocks of which we cite four (Hauri et al., 2014; Li and Millikin, 2014; Robinson et al., 2014; Tartèse et al., 2014) as representative.

7 CONCLUSIONS

We have shown that worldwide observations of SWS throughout the Earth's crust and upper mantle demonstrate that the remarkable linearity of the Gutenberg-Richter relationship is caused by the criticality of the pervasive distributions of stress-aligned fluid-saturated microcracks. Thus the physics underlying the linearity of Gutenberg-Richter is that earthquakes occur when the pervasive microcracks in the critical-system are so closely-spaced that they reach fracture-criticality, and lose shear-strength, so that the rock fractures if there is any disturbance. Since the stress-accumulation before earthquakes can be monitored by SWS, a linear Gutenberg-Richter implies that the time, magnitude, and estimated location of impending can be stress-forecast.

Since deep moonquakes (DMQs) from repeated hypocentral nests of DMQs also possess a linear Gutenberg-Richter relationship (although the different b values imply different magnitude-frequency relationships) implying that fluid-filled microcracks are also present in lunar rocks. Consequently, we suggest that DMQs with Gutenberg-Richter is a direct indicator of 'patches' of residual fluids at depth within the Moon.

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