an excerpt from

# 52 THINGS YOU SHOULD KNOW ABOUT GEOPHYSICS

EDITED BY MATT HALL & EVAN BIANCO

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First published in 2012 by Agile Libre
Nova Scotia, Canada. *www.agilelibre.com*

*Technical editors* Matt Hall & Evan Bianco • *Managing editor* Kara Turner
*Designer* Neil Meister, MeisterWorks • *Indexer* Linda Lefler
*Cover design* electr0nika • *Printing* Amazon CreateSpace

**Library and Archives Canada Cataloguing in Publication**

52 things you should know about geophysics / edited by Matt Hall and Evan Bianco
Includes bibliographical references and index.

ISBN 978-0-9879594-0-9

1. Geophysics. I. Hall, Matt, 1971- II. Bianco, Evan, 1982-
III. Title: Fifty-two things you should know about geophysics.

QC806.F54 2012 550 C2012-902408-2

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# Colophon

This book was compiled in Google Docs and Microsoft Word, and laid out on a Mac using Adobe InDesign with the MathMagic plug-in. The cover typeface is Avant Garde Gothic and the text typefaces are Minion and Myriad. The figures were prepared in Inkscape. It was published through Amazon's CreateSpace.

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# Old physics for new images

## Evan Bianco

At its core, seismology is concerned with how objects move when forces act on them. Over 300 years ago, two gentlemen outlined everything we need to know: Robert Hooke, with his law describing elasticity, and Isaac Newton with his second law describing inertia. Anyone working with seismic data should try to develop an intuitive understanding of their ideas and the equations that manifest them.

For rocks, a rudimentary but useful analogy is to imagine a mass suspended by a spring. Hooke discovered that when the spring is stretched, stress is proportional to strain. In other words, the force vector **F** exerted by the spring is proportional to the magnitude of the displacement vector **u**. The proportionality constant *k* is called the stiffness coefficient, also known as the spring constant:

$$\mathbf{F} = -k\mathbf{u}$$

This is the simplest form of Hooke's law of elasticity. Importantly, it implies that the stiffness coefficient is the defining property of elastic materials.

Newton's second law says that a body of mass *m*, has a resistance to acceleration $\ddot{\mathbf{u}}$ (that is, the second derivative of displacement with respect to time) under an applied force **F**:

$$\mathbf{F} = m\ddot{\mathbf{u}}$$

If displaced from equilibrium, a mass attached to the end of a spring will feel two forces: a tensional force described by Hooke's law, and an inertial force from its motion, described by Newton's second law. The system of a mass and a single spring yields simple harmonic motion, characterized by acceleration being proportional to displacement but opposite in direction:

$$m\ddot{\mathbf{u}} = -k\mathbf{u}$$

Simple harmonic motion has many applications in physics, but doesn't quite fit the behaviour of rocks and seismic waves. A rock is bounded, like a mass held under the opposing tension of *two* springs. In this case, there are two tensional forces acting in the line along which the mass can oscillate. Writing

*Rock properties dance upon the crests of travelling waves, and they dance to the tune of seismic rock physics.*

out the forces in this system and doing a bit of calculus yields the well-known wave equation:

$$\ddot{\mathbf{u}} = \frac{k}{m} \nabla^2 \mathbf{u}$$

The wave equation says the acceleration of the mass with respect to time is proportional to the acceleration of the mass with respect to space, a tricky concept described by the Laplacian $\nabla^2$. The point is, the only properties that control the propagation of waves through time and through space are the elasticity of the springs and the inertia of the mass.

Some vector calculus can move our spring–mass–spring system to three dimensions and unpack $k$, $m$, and $\nabla^2$ into more familiar earth properties:

$$\ddot{\mathbf{u}} = \frac{\mathbf{F}}{\rho} + \left[\frac{\lambda + 2\mu}{\rho}\right] \nabla(\nabla \cdot \mathbf{u}) - \left[\frac{\mu}{\rho}\right] \nabla \times (\nabla \times \mathbf{u})$$

Here, $\lambda$ and $\mu$ are the Lamé parameters, representing Hooke's elasticity, and $\rho$ is the density of the medium, representing Newton's inertia. You don't need to fully comprehend the vector calculus to see the link between wave mechanics, as described by the displacement terms, and rock properties. I have deliberately written this equation this way to group all the earth parameters in the square brackets. These terms are equal to the squares of P-wave velocity $V_\mathrm{P}$ and S-wave velocity $V_\mathrm{S}$, which are therefore nothing but simple ratios of tensional ($\lambda$ and $\mu$) to inertial properties ($\rho$).

To sum up, the Lamé parameters and density are the coefficients that scale the P-wave and S-wave terms in the wave equation. When rock properties change throughout space, the travelling waveform reacts accordingly. We have a direct link between intrinsic properties and extrinsic dynamic behaviours. The implication is that propagating waves in the earth carry information about the medium's intrinsic parameters. Rock properties dance upon the crests of travelling waves, and they dance to the tune of seismic rock physics.

# The magic of Lamé

## Bill Goodway

*If geophysics requires mathematics for its treatment,*
*it is the earth that is responsible not the geophysicist.*
**Sir Harold Jeffreys**

This quote was offered as a disclaimer on a course I took at the University of Calgary in 1988: Dr Ed Krebes' Geophysics 551 *Seismic Techniques*. This excellent course was pivotal in my enlightenment regarding Lamé's parameters. I repeat the quote here as it disclaims my seemingly unnecessary obfuscation in the use of equations that follow.

The basic earth parameters in reflection seismology are P-wave velocity $V_P$, and S-wave velocity $V_S$. However, these extrinsic dynamic quantities are composed of the more intrinsic rock parameters of density and two moduli terms, lambda ($\lambda$) and mu ($\mu$), introduced by the 18th-century French engineer, mathematician, and elastician Gabriel Lamé. Lamé also formulated the modern version of Hooke's law relating stress to strain as shown here in its most general tensor form:

$$\sigma_{ij} = c_{ijkl}\,\varepsilon_{kl} = (\lambda\delta_{ij}\,\delta_{kl} + \mu\delta_{ik}\,\delta_{jl} + \mu\delta_{il}\,\delta_{jk})\,\varepsilon_{kl}$$

Here, $\sigma_{ij}$ is the $i$-th component of stress on the $j$-th face of an infinitesimally small elastic cube, $c_{ijkl}$ is the fourth rank stiffness tensor describing the elasticity of material, $\varepsilon_{kl}$ is the strain, and $\delta_{ij}$ is the Kronecker delta. The adage 'stress is proportional to strain' was first stated by Hooke in a Latin anagram *ceiiinosssttuv*, whose solution he published in 1678 as *Ut tensio, sic vis* meaning 'As the extension [strain], so the force [stress].' Despite being interestingly reversed and non-physical, Hooke's pronouncement is illustrated here with complete mathematical rigor, and this equation creates the basis for the science of materials, including rocks. Interestingly, and most notably, only Lamé's moduli $\lambda$ and $\mu$, appear in this equation; not bulk modulus, Young's modulus, Poisson's ratio, $V_P$, $V_S$, or any other seismically derived attribute.

The methods to extract measurements of rocks and fluids from seismic amplitudes are based on the physics used to derive propagation velocity. This derivation starts with Hooke's law and Newton's second law of motion, and yields a set of partial differential equations that describe the progression of a seismic

*The methods to extract measurements of rocks and fluids from seismic amplitudes are based on the physics used to derive propagation velocity.*

wave through a medium. It also forms the basis of AVO-based descriptions of the propagating medium.

The P-wave propagation of a volume dilatation term $\theta$ derived from Hooke's law is:

$$\rho \frac{\partial^2 \theta}{\partial t^2} = (\lambda + 2\mu)\nabla^2 \theta$$

and the S-wave propagation of the shear displacement term $(\nabla \times u_{\text{sh}})$:

$$\rho \frac{\partial^2 (\nabla \times u_{\text{sh}})}{\partial t^2} = \mu \nabla^2 (\nabla \times u_{\text{sh}})$$

The vector calculus in these equations says that the particle or volume displacement for a travelling P-wave in the earth is parallel to the propagation direction (as $\nabla \times \theta = 0$), whereas the particle displacement imposed by a passing S-wave is orthogonal to the travelling wavefront. Consequently, the intuitively simple Lamé moduli of rigidity $\mu$ and incompressibility $\lambda$ afford the most fundamental and orthogonal parameterization in our use of elastic seismic waves, thereby enabling the best basis from which to extract information about rocks within the earth.

These Lamé moduli form the foundation for linking many fields of seismological investigation at different scales. Unfortunately the historical development of these fields has led to the use of a wide and confusing array of parameters, which are usually complicated functions of the Lamé moduli. None of these are inherent consequences of the wave equation, as the Lamé moduli are. This includes standard AVO attributes such as intercept and gradient or P-wave and S-wave reflectivity that are ambiguous and complex permutations of Lamé moduli $\lambda$ and $\mu$, or Lamé impedances $\lambda\rho$ and $\mu\rho$. Many other parameters such as Poisson's ratio and Young's modulus have arisen due to inappropriate attempts to merge the static un-bound domain of geomechanics to the dynamic bound medium of wave propagation in the earth. These attempts have resulted in the use of contradictory assumptions, which are completely removed when restating equations using the magic of Lamé moduli.