# PETER STYLES INTRODUCING GEOPHYSICS





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# **Introducing Geophysics**

**Peter Styles** 



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#### **Preface**

If you want to learn what is beneath the Earth's surface, I guess the obvious thing to do is to drill a hole; but the deepest borehole to date, at just over 12 km, is on the Kola Peninsula in Russia, which is certainly a long way down; but this is rather like a doctor sticking a pin in your hand just beneath the skin and trying to work out how the body works. We can look at what emerges from volcanoes (a noble pursuit, I have to add) but again that is the medical equivalent to looking at the unmentionable products of skin eruptions!

A cynical but probably truthful adage is: 'a borehole tells you absolutely everything about absolutely nowhere'. The distance to the centre of the Earth is 6400 km, but sadly as we can't do a Jules Verne and go there, we must resort to craftier methods. Those are what constitute GEOPHYSICS in all of its manifestations, which I will spend some time explaining to you in this book. The medical analogy can be extended, in that nowadays a doctor will use imaging scans of various kinds: ultrasound, electrical, X-ray, to determine body structure; and that is how we explore the Earth. It is not an exaggeration to say that almost everything we know about the interior of the Earth has emerged from geophysical research.

When I went to university in 1969, from a small fishing and mining town in Northumberland and a local grammar school, I never intended to be a geophysicist. I intended to be a nuclear physicist, but discovered during my BA Hons (Phys) at Oxford that nuclear physics wasn't quite as fascinating as I had once fondly imagined; and besides, in Blackwell's I had bought a book called Global Geophysics by Tucker, Cook, Iver and Stacey which, at a stroke, changed my intended destination! It turned out, thank God, that you could understand most of the Earth with classical physics: gravity, magnetism, heat, light and sound! I then spotted a PhD in the School of Physics at the University of Newcastle-upon-Tyne on the revolutionary new ideas of plate tectonics, as applied to the Red Sea and East African Rift: this promised exotic travel and new ways of thinking about the Earth. It was great fun going to sea on RRS Shackleton to the Indian Ocean and the Red Sea, and

working in the Eastern Desert of Egypt. So, I owe my long career to a book. I guess that's why you agree to write other books yourself, as you hope that you might provide that 'Road to Damascus' moment for someone else!

However, sometimes after getting so far into the manuscript that you wonder 'why did you ever start writing this', you stand back and have a think about it. In my case it seemed like an opportunity to reprise *everything* that I have ever taught anyone about geophysics. I started a lectureship at Swansea University Geology Department straight from my PhD in 1977. In my welcome meeting with the Head of Department, Professor Derek Ager, I received the following instruction: 'In a week's time teach all of plate tectonics' to the new first year class of 100-plus fresh-faced students; their FIRST lecture and MY first lecture! As that was essentially my PhD, I managed to deliver that task after an intense period of very late nights assembling the material into coherent lectures. In short order, that first year, I then taught the whole spectrum of applied and exploration geophysics (oil, gas, mining, engineering) at introductory and advanced levels to second- and third-year students. What I didn't know myself - and there was quite a bit of that - I had to learn very quickly from a limited number of available geophysics textbooks.

Being the only geophysicist in quite a large geographical area of south-west Wales is a two-edged sword, in that you have to be a jack-of-all-trades, but there isn't much competition. As well as being a teacher and researcher, I also became a competent geophysical consultant in site investigations and geohazards: landslides, sinkholes, induced earthquakes and associated catastrophes in coalmines, and soon had a research group working on these subjects, as well as continuing with my global tectonics research.

This book attempts, while keeping most maths out of the way, to communicate some of the fun that geophysics has given me for more than 40 years, in what I hope is an accessible manner. I can only hope that I have succeeded.

#### **Acknowledgements**

I owe a great deal to my PhD supervisor and friend, the late Professor Ron Girdler, who taught me to be a scrupulous researcher. I owe my wide spectrum of geophysical experience to my first Head of Department, Professor Derek Ager, an internationally renowned palaeontologist, who said when I started the job, 'I don't know anything about geophysics, so teach them what you think they should know'; which I did, and this book reflects that breadth of material. I must thank all of my valiant geophysical technical staff and postgraduates who laboured in all kinds of foul weathers: camping in swamps beneath glaciers in Chile, sweltering in deserts measuring gravity in Egypt, digging holes for seismometers on Scottish hillsides in blizzards, amongst many other indignities. They never complained, and we had many a refreshing beer and a laugh in pubs and tents after those tiring evenings. The many undergraduates I taught now often keep in touch in these days of Facebook; many became geophysicists by trade, and I thank them for listening to (most of) my lectures from the chalk and talk days, through overhead projectors to PowerPoint.

Finally, I owe an enormous debt of gratitude to my dear wife Roslyn, and to my children, who often had to manage without me because I was doing geophysics somewhere else, and still ended up as wonderful people, thanks to her. For the last year she has endured me sitting in my study typing and moaning while I wrote down what I thought you, the reader, should know about geophysics.

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#### Introduction and scene setting

It is often said, at least in geological circles, that 'if you can't grow it, then you must mine it': and although that isn't such a popular adage these days, it must be realised that there only two places either to 'get stuff' or 'put stuff' and that is either above or BELOW ground. This obviously encompasses resources (hydrocarbons especially, but also industrial minerals, and in some circumstances, water), but also the question of where we might store, either temporarily or permanently, **radioactive waste** and **carbon dioxide**.

We become used to thinking about the interior of the Earth as being that bit just beneath our feet, or perhaps that which can be accessed by mining, either of coal or resource metals and minerals, or even perhaps from the results of a deep borehole; but few of us appreciate that even a borehole 5 km deep (quite a deep and expensive venture) is only sampling much less than one-tenth of a per cent of our spherical Earth. I realise that some folk may challenge that 3-D assumption, although it is based on many observations.

If we want to learn what is present, and indeed, what is happening deeper down, we have to resort to the discipline that has engaged me as a professional scientist and academic for more than 40 years now: **geophysics**. You may already have come across geophysics, albeit mentioned in a slightly disparaging tone, from programmes such as *Time-Team*: where folks in wellies and daft hats call for some 'geofizz' to detect archaeological remains, or sometimes, and more grisly, human remains and the evidence of their burial, in forensic geophysics.

Geophysics is simply the physics of the Earth, and as the Earth is very large and relatively slow-moving (we will come to rotation rates later), we can mostly get by with classical physics: heat, gravity, magnetism, electricity, vibrations and waves (of various kinds), and without the intricacies of quantum physics and relativity. It was rather reassuring that in most of geophysics, albeit then a subject in its relative infancy, you could get by with 'Heat, Light and Sound' together with quite a bit of maths. In fact, as described in the Preface, I changed over to geophysics when I discovered the delights and wonders of **plate tectonics** – the concept we will delve into more deeply in a while.

For quite a long while, I was what might be called a 'pure' geophysicist, i.e. working on problems and issues that transcended the day-to-day. I soon realised that there was more to geophysics than simply defining the parameters of the whole Earth, and that industries were already using geophysics to hunt for oil, to detect the location of metalliferous ores, and even, in a fairly crude way, helping to inform engineering and construction about the nature of the shallow Earth and its many construction pitfalls and geohazards. I was also approached, as 'the geophysicist' in the whole of south-west Wales, to attempt to use geophysics to find solutions to the problem of catastrophic and fatal methane emissions into south Wales coalmines. So, in parallel with my lofty aspirations, I became, through force *majeure*, engaged with what I guess, by analogy, might be called 'impure geophysics', but which was really applied geophysics - which was indeed where many of my own students obtained jobs, and which has metamorphosed into applied and environmental geophysics, where I have spent most of my life. But – and this is important – the physics and the maths were just the same.

In this book, therefore, (without too much of the underlying mathematics), I shall attempt to explain the beauty of geophysics, and how through it we can learn about the deep interior of the Earth, and also understand the shallower bits where we get our resources, live, and build our houses. I will make no attempt to be comprehensive, as the subject has already filled books ten times the size of this one, but I will refer you to places where you can delve deeper. I hope to give you the feel, smell and taste of geophysics and the interesting places it can take you. I make no apologies if the examples I give you are often taken from my own work, as they are the ones I understand the best. It is tempting, and indeed, I originally intended, to include chapters on various geophysical

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phenomena such as **seismology**, **gravity**, and **magnetics**, and in each chapter to have a short section on the use of that technique in the real world; but in fact, exploration and environmental geophysics are problem-driven rather than technique-driven, and often a combination of techniques will work best. Therefore, I shall keep those aspects until the end, as by then we will have a feel for all of the tools that are available to us, and their application will make more sense.

It would also be nice for all of our concepts concerning the Earth to emerge in the correct time order, and with a focus on the disciplines that shone light on them; but this is a short book and we need to be able to use words and ideas early on, so I aim to give you a rudimentary picture of what geophysics has revealed about the Earth and its structures, so that we can then put flesh on the bones vis-à-vis various aspects of the subject. If you are interested enough to be reading this book, then you will almost certainly be familiar with them, if only in outline, and so I hope not to be giving too much of the game away.

The Earth is a more or less spherical planet (more on that later), rotating on its axis every day and orbiting around our Sun every year, which is how we measure our cycles of night/day, winter/summer. It leans over slightly at about 23°, which gives us our seasonal variations. It is not a uniform sphere, though; it is a set of concentric shells. The outer shell is, of course, called the **crust** and there are two flavours of that: oceanic crust, which lies mainly beneath the oceans and is relatively young (less than c.200 million years) and varies in thickness from zero to c.10 km; and continental crust which, as the name gives away, is mainly beneath the continents but extends a little way beneath the edges of the oceans. This can be very, very, old (more than 4000 million years) or relatively young, potentially only a few million years, and sometimes indeed VERY young (e.g. erupted from a volcano yesterday), and varies in thickness from a few kilometres in certain stretched areas to c.70 km. This continental crust is very important to us, as it is where most of us live and where we get much of our resources; it is mainly made of silicon and aluminium oxides, which is why in old books it is often called SIAL.

The next layer down, the **mantle**, is the largest part of the Earth by volume at about 85%, and is a little less than 3000 kilometres thick. It is made of rock but has a different

chemical composition and mineralogy to the crust, consisting mainly of silicon- and magnesium-rich compounds, so it was called SIMA. We sometimes see bits of it brought to the surface in rare places and after rare events, but most of what we know about it has been discovered by geophysics of one sort or another. In fact, there are several divisions within the mantle that are controlled by different mineral phases and with differing mechanical properties, which we will discuss in a short while.

However, beneath the mantle it gets odder still as we enter what we call the **core**. We cannot visit the core, despite what Hollywood would have you believe, and although it is also about 3000 kilometres thick, it occupies much less of the volume of the Earth, at about 15%. That 15% has some marvellous properties, though, and we believe that at one time it was composed of completely molten iron and nickel alloys with some other exotic constituents. The interior part of the core has solidified over its 4500-million-year lifetime due to the enormous pressures that exist there, but the outermost part is still molten, as we will see from seismology in a later chapter, and it is there that we find the origin of the **Earth's magnetic field**, which we will also explore in some detail in a later chapter.

The various layers, primarily distinguished by their chemistry, are displayed on the left-hand side of Figure 1.1



**Figure 1.1** Division of the Earth into layering on the basis of a) chemical changes, i.e. crust, mantle core (left); b) strength and rheology changes, i.e. lithosphere, asthenosphere, mesosphere and core.

Another way of looking at the Earth's structures, though, is on the basis of their mechanical properties, i.e. their strength, which is shown on the right-hand side of Figure 1.1. We have already divided the core, so we won't discuss that again; but the main differences come in the upper part of the mantle where we insert a weak layer called the asthenosphere (asthenos is Greek for weak or yielding) into the upper mantle at a depth of between 100 and c.200 kilometres. The evidence for this comes again primarily from seismology, but with a bit of gravity thrown in. Overlying the whole shebang is a stronger, rigid and cooler layer on which both oceanic and continental crust ride as passive passengers, and we call this the **lithosphere** (*lithos* is Greek for strong). We sometimes call the rest of the mantle the mesosphere under this mechanical designation, but this term is not much used.

Of course, once we are prepared to look at the Earth in this way, we are ready for plate tectonics. It now seems

blindingly obvious that the outer layers of the Earth are still moving relative to each other, and that the areas where they move apart, where they move together, and where they slide past each other are of enormous significance – but this was not always the case.

A quick glance at the shape of the continents around the North and South Atlantic strongly suggests that they must, at one time, have fitted together; and there are many more examples of such geometric fits. Alfred Wegener, a German polar scientist, was puzzled by the distribution of fossils, particularly plants but also of land reptiles, and by geological trends and rock types, and pointed out that these all matched much better if we moved the continents all back together as in Figure 1.2, with everything wrapped neatly around Africa, and joined them at their 200 m depth contour, rather than the present continental edge *sensu stricto*. His major work *Die Entstehung der Kontinente und Ozeane*, 'The origin of Continents and Oceans', came



Figure 1.2 Alfred Wegener's fit of the continents around the Atlantic with the fits of fossil types indicated. (after USGS)