IN THE ZONE

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1811-5209/16/0151-$0.00 DOI: 10.2113/gselements.12.2.151

The New Year of 2016 opened with a great flurry of activity on the Mineralogical Society of America's on-line discussion board 'MSA-talk' about the teaching of crystallography. More members rushed to their keyboards to contribute on this topic than on any I can remember. I confess I didn't read all the contributions, but I think a reasonable one-line summary would be 'find a method that works for you and stick to it'. In the UK, crystallography has lost its place in the foundations of geology courses, often on the grounds that it will scare off students who will gravitate towards courses they believe will be less demanding. In fact, as many will discover, at the level they are expected to achieve in geology courses, the explicit solutions to relatively simple crystallographic problems are much more easily obtained than deep understanding of complex, multi-facetted topics like the history of mountain belts and terrane assembly.

I taught crystallography (among other things) for 40 years, and always enjoyed it. At the start of my career I was dropped in at the deep-end when, in 1964, I got a lectureship at the University of Aberdeen, in north-east Scotland, where crystallography was a major part of the curriculum for geology students. The one man-in-charge was Professor of Geology and Mineralogy, Thomas Crawford Phemister (1902–1982), an austere Scot who usually came to work in a black jacket, pin-striped trousers, white shirt and silver tie. In the brief, cool Aberdeen summer he chilled-out by appearing in a beige linen tropical suit.

Phemister graduated from Cambridge University (UK) in the 1930s, when crystallography was in its heyday, and he certainly saw it as the core of geology. He was a brilliant man, but wrote only 10 papers, on a mix of crystallography and geological topics, including a long review of the 'Sudbury Irruptive' (Canada). The most remarkable was published in *American Mineralogist* in 1954 and is entitled 'Fletcher's indicatrix and the electromagnetic theory of light'. In it, Phemister shows, for the benefit of the 'enquiring student' (!), how the indicatrix can be deduced from Maxwell's electromagnetic equations, and then how Maxwell's equations can be derived from Fletcher's indicatrix. The presentation is 'much simplified by using the abbreviated notation of Cartesian tensors', but there are still 20 pages of equations with very little text. The paper ends with a three-line equation. There is no concluding text and no acknowledgements. Sadly, but perhaps unsurprisingly, this tour-de-force has been rewarded by only three citations.

As a fresh young lecturer whose interests were mainly in petrology, I advanced into this hot-house of crystallography with much trepidation. Course content was firmly prescribed by the professor. At second-year level, where I did most of my crystallography teaching, the first practical activity for each student was to measure the interfacial angles of a crystal using an optical goniometer, plot a stereogram, index the face-poles and calculate the axial ratio. The crystals were usually about 5 mm in length; the quartz crystal in my photograph is 40 mm long, and used only for illustration (Fig. 1).

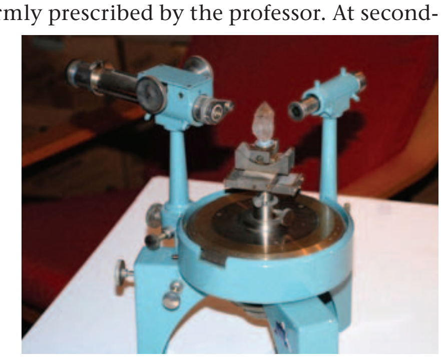

Figure 1 A Unicam single-circle optical goniometer, like the one described in the text. The quartz crystal here is much larger than those I used for teaching.

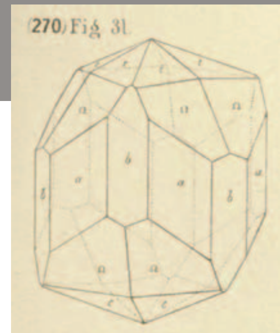

Figure 2 Crystallographic drawing (derived from goniometer measurements) of a Scottish calcite crystal. From Heddle's *Mineralogy of Scotland* (1901).

A special, windowless room was assigned for this purpose, fitted out with tall tables beside which the students would stand for 3 hours per week for 4 weeks. Because the number of goniometers was less than the number of students, I spent 24 hours of each year in nearly complete darkness while the students snuffled and muttered and cursed as they strove to finish their assignment. As the crystals were rotated, the signals reflected from the faces shone on the walls and moved like miniature searchlights, some in the plane of the turntable, but too many describing sine waves around the walls.

For readers who inhabit only the mainly scalar world of geochemistry, I have inserted a drawing of a crystal of calcite (Fig. 2) from the magnificent two-volume work by Matthew Forster Heddle (1828–1897), *The Mineralogy of Scotland*, published posthumously in 1901. The mighty Heddle has featured in an *Elements* Parting Shots column before (Parsons 2010). To measure an interfacial angle you have to set the edge direction between any two faces exactly vertical, using the arcs. Once you have one edge vertical you will find parallel edges and will have located a zone of faces that you can plot on a great circle. Their common edge direction is the zone axis. This is relatively easy for the prism zone (the set of faces labelled *a, b, a, b,...* on Heddle's drawing), but it is much harder to find inclined zones and usually means removing the crystal from its bed of plasticine (soft modelling clay) and replacing it at an angle to the turntable.

Fortunately, I had done a lot of single-crystal X-ray diffraction work on feldspars during my PhD programme. I certainly was not, and never have been, an expert crystallographer, but I could find a zone axis and set it vertical, however obscure and inclined, in the twinkling of an eye, as if by magic. So, when a student was clearly beginning to suffer unsustainable levels of stress, I would stroll over in the gloom and tell him or her to watch while I performed this trick. Unfortunately, because the student couldn't look through the horizontal telescope as I performed, the exact manipulations still remained mysterious. But they would have another great circle on their stereogram, and, rejuvenated, would forge ahead!

Was this 12-hour ordeal a waste of time? I think not. It was fine training in a tricky, manipulative technique, and in careful recording of measurements, early in the student's course. When the penny dropped and they suddenly understood, the pleasure was palpable, and mutual. There is no better way to understand stereograms than to construct one for your own crystal, and because the major zone axes often correspond with the cell edge directions, students could make the connection between cell edge directions and the crystal's lattice. The lecture course progressed system by system, starting with the triclinic and plotting an exact stereogram of a real example of the holosymmetric class of each system, calculating Miller indices, exact axial ratios and angles, applying Napier's spherical trigonometry and arcane devices like the anharmonic ratio of four tautozonal faces. Students deduced all the reduced symmetry point groups in each system using sketch stereograms and figured out all the two-dimensional triclinic, monoclinic and orthorhombic space groups by experiment. After some months of this we started to look at real minerals. Those were the days!

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