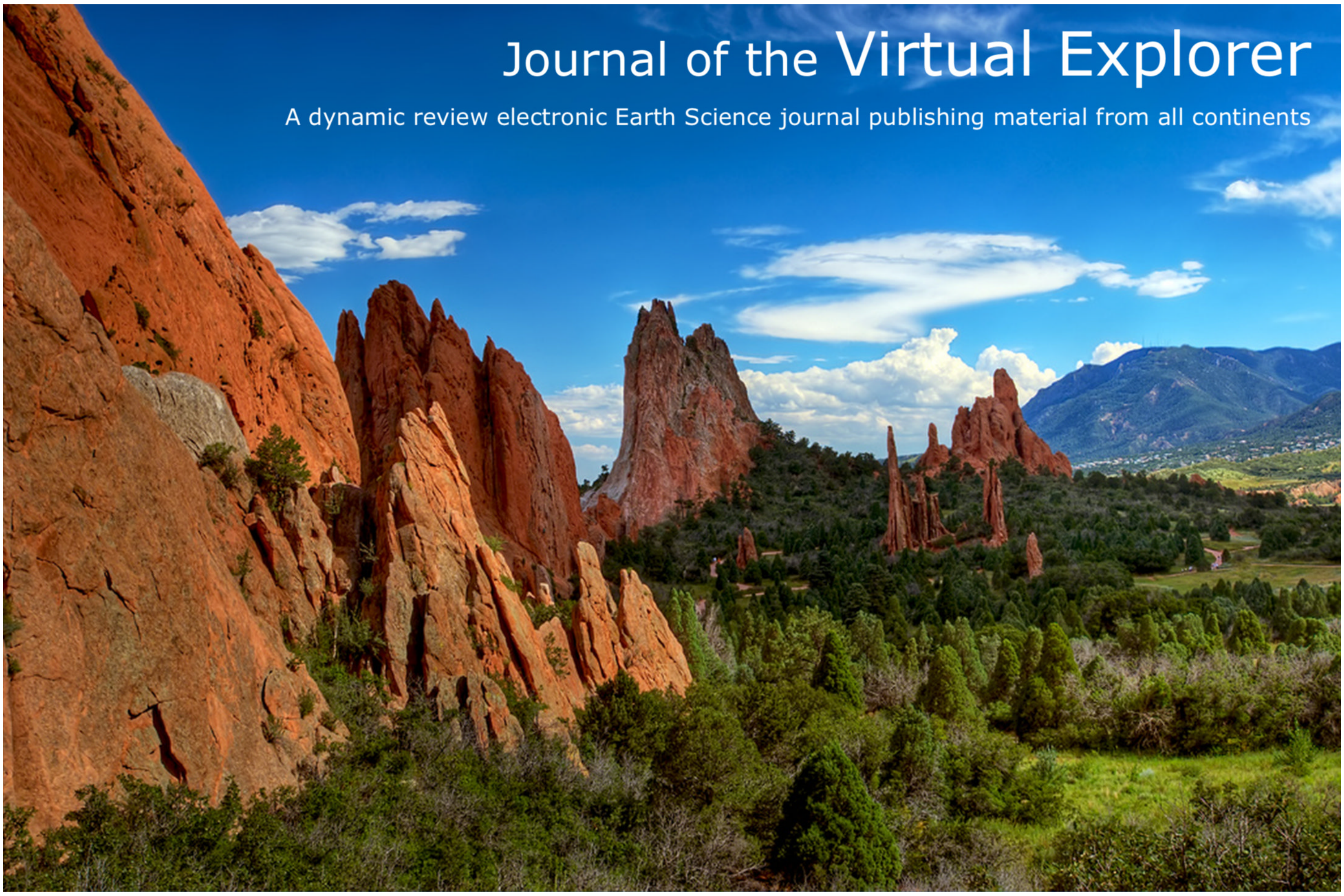


Visualization of Magmatic Emplacement Sequences and Radioelement Distribution Patterns in a Granite Batholith: An Innovative approach using Google Earth.

Ronán W. Hennessy, Martin Feely

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **29**, paper 3
In: (Ed.) Declan De Paor, Google Earth Science, 2008.

Visualization of Magmatic Emplacement Sequences and Radioelement Distribution Patterns in a Granite Batholith: An Innovative approach using Google Earth.

Ronán W. Hennessy, Martin Feely

Journal of the Virtual Explorer, Electronic Edition, ISSN 1441-8142, volume **29**, paper 3
In: (Ed.) Declan De Paor, Google Earth Science, 2008.

Abstract: Geochronometric data pertaining to the emplacement stages of the late-Caledonian granites of Connemara, western Ireland indicate a sequential emplacement of the granite over approximately a 40 Ma time period. Using the Google Earth time-slider functionality, a series of Keyhole Markup Language animations have been generated to demonstrate the capabilities of Google Earth in the communication of 4D geological visualizations. Inverse-distance weighted interpolation of gamma-ray spectrometric measurements recorded over the Galway Granite batholith enabled the generation of a series of radioelement maps that are presented in Keyhole Markup Language format. The maps show the surface distribution of the radioelements K, U, Th and the surface heat production throughout the batholith. The ability to merge the two data sets in an openly accessible 3D earth viewer application demonstrates the potential of Google Earth for geoscientific visualization.

Google Earth files. These links will launch Google Earth (if enabled).

1. Google Earth Emplacement Maps

2. Google Earth Geochemical Maps

http://virtualexplorer.com.au/article/2008/196/patterns-in-a-granite-batholith-using-google-earth

Citation: Hennessy, R., Feely, M. 2008. Visualization of Magmatic Emplacement Sequences and Radioelement Distribution Patterns in a Granite Batholith: An Innovative approach using Google Earth.. In: (Ed.) Declan De Paor, *Journal of the Virtual Explorer*, volume **29**, paper 3, doi: 10.3809/jvirtex.2008.00196

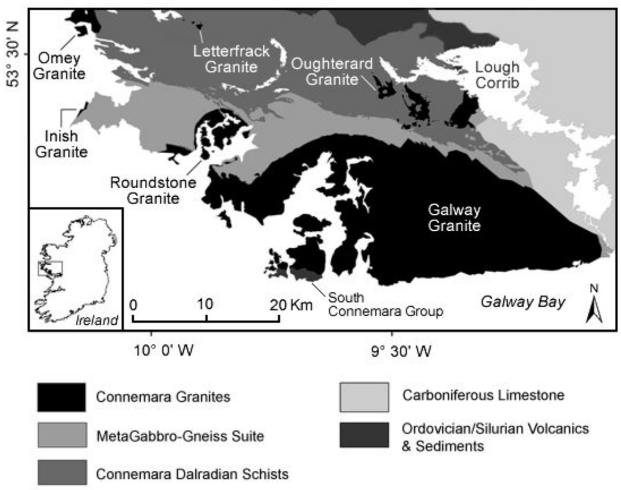
Introduction

This paper demonstrates the capabilities of Google Earth (earth.google.com) in communicating multi-faceted information pertaining to the sequential emplacement, during approximately a 40 Ma time period, of late-Caledonian granites in Connemara, western Ireland. We generated a granite emplacement animation using a combination of 1:10,560 scale granite bedrock maps (Feely *et al.* 2006) and TIMS U-Pb single zircon and Re-Os molybdenite geochronometry data (Feely *et al.* 2003; Selby *et al.* 2004; Feely *et al.* 2007). The 4D visualization of the emplacement stages of the Connemara granites employs the Google Earth time-slider functionality. In addition to the granite emplacement maps, a series of geochemical maps relating to the Galway Granite are presented. This radioelement data has been digitized, georeferenced and interpolated in a GIS, and rendered in Keyhole Markup Language (KML) format for visualizing in Google Earth. Inverse-distance weighted (IDW) interpolation methods were applied to the surface spatial distribution of the radioelements K, U and Th (Feely and Madden 1986; 1987) for the production of a series of gridded raster maps. This study builds on the some of the methods of past studies (Feely and Madden 1987; Madden 1987; Feely and Madden 1988) and attempts to augment the final stage of presenting the data in a visually compelling and widely accessible format using Google Earth.

Geological Background

The Galway batholith and its satellite granites (Omey, Letterfrack, Inish and Roundstone granites) located in Connemara are important elements of the late-Caledonian geological history of western Ireland and occupy a key location along the North Atlantic Caledonides (Figure 1). The Galway batholith is a calc-alkaline granite body and was emplaced into the 474.5-462.5 Ma Metagabbro-Gneiss Suite to the north (Leake 1989; Leake and Tanner 1994; Friedrich *et al.* 1999), and into Lower Ordovician greenschist facies rocks (the South Connemara Group) to the south (McKie and Burke 1955; Williams *et al.* 1988). The batholith emplacement postdates the Skird Rocks Fault (Figure 2), which Leake (1978) considers to be a splay off the Southern Uplands Fault and to have strongly influenced its siting creating a stitching pluton. The batholith extends for several kilometers beneath the Carboniferous rocks of the Galway Bay area, as indicated on gravity and aeromagnetic maps (Murphy 1952; Max *et al.* 1983; Madden 1987). The long axis of the batholith is oriented WNW-ESE, oblique to the E-W strike of the Skird Rocks Fault. Two major faults zones, the NNE-trending Shannawona Fault Zone (SFZ) and the NW-trending Barna Fault Zone (BFZ), define the boundaries between the western, central and eastern blocks in the batholith. The SFZ represents a fundamental litho-geochemical discontinuity in the mid-western region of Galway Granite batholith.

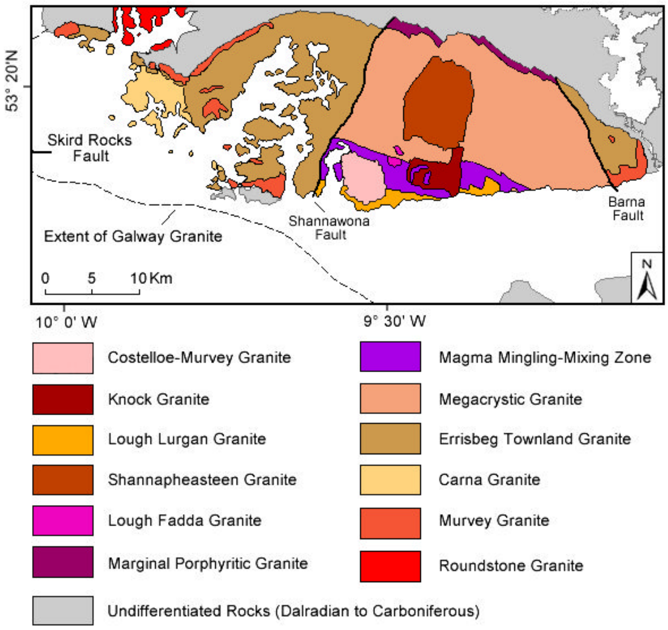
Figure 1. Regional Geology of western Ireland.



Regional Geology of western Ireland.

The western and eastern blocks expose granodiorite through granite to alkali granite (Leake 1978). The central block granites have been described in detail by the following: Feely and Madden (1986, 1987, 1988), Whitworth and Feely (1989, 1994), Feely *et al.* (1989, 1991), El Desouky *et al.* (1996) , Crowley and Feely (1997), Graham *et al.* (2000), Baxter and Feely (2002) and Baxter *et al.* (2005). Baxter *et al.* (2005) interpret fabrics within the Megacrystic Granite and Magma Mixing-Mingling Zone (MMZ) Granodiorite to reflect ballooning processes operating in successive magma batches (e.g. Megacrystic Granite and MMZ Granodiorite) at the emplacement level. Leake (2006) states that centre and northern margin of the batholith exposes field evidence indicating that the approximately 400 Ma main phase of emplacement was incremental by progressive dyke injection and stoping of the Metagabbro-Gneiss Suite. These earlier granite batches were stoped by the later granite intrusions such as the Costelloe-Murvey Granite (CMG) during a brittle fracture regime (Crowley and Feely 1997). The central block exposes a juxtaposition of earlier deeper level granites with late-stage higher-level granites. The satellite plutons i.e. Roundstone, Omey, Inish and Letterfrack are located to the north and northwest of the batholith (Townend 1966; Leake and Tanner 1994). The Roundstone and Omey plutons are circular granite plugs with diameters of approximately 6 to 7 km. The Inish granite is located offshore with its eastern edge exposed along the western seaboard. The Letterfrack granite comprises three outcrops, which probably represent one pluton in northwest of the Connemara metamorphic complex.

Figure 2. Regional Geology of the Galway Granite Batholith



Regional Geology of the Galway Granite Batholith

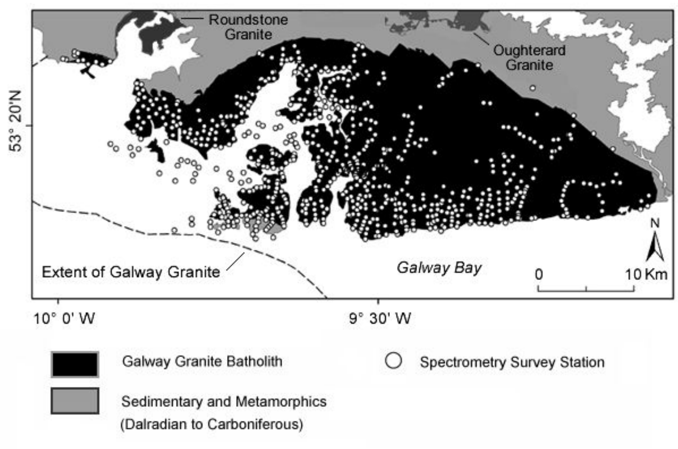
Geochronology

When U-Pb zircon age determinations, using thermal ionization mass spectrometry (TIMS) by Feely *et al.* (2003) are combined with Re-Os molybdenite age determinations (Feely *et al.* 2003; Selby *et al.* 2004; Feely *et al.* 2007), a Connemara granites' emplacement sequence ranging over approximately 40 Ma emerges. Granite magmatism began in the Connemara sector of the orogen with the ascent and emplacement of the satellite Omey granite at approximately 422 Ma (Feely *et al.* 2007). The age of emplacement of the other satellite plutons is uncertain, however in the case of the Roundstone granite unpublished field evidence indicates that it predates the batholith (Leake pers comm.). Friedrich *et al.* (1999) suggest that resetting of mica ages to 415 Ma in the country rocks are due to the heat from the granite. We assume therefore that the four satellites were emplaced pre-410 Ma. Re-Os ages for granite related molybdenite mineralization at the western end of the Galway Batholith (Feely *et al.* 2003; Selby *et al.* 2004) yield ages of between 407 (Murvey) and 410 Ma (Mace Head). Pidgeon (1969) determined a bulk zircon age of 412 ±15 Ma for the Carna granite which hosts the molybdenite bearing quartz veins at Mace Head. The main body of magma, the Galway Batholith was emplaced between 410 Ma and 380 Ma (Feely *et al.* 2003). The Oughterard Granite, dated at 462.5 ±1.2 Ma (Friedrich *et al.* 1999) and outside of the aforementioned approximate 40 Ma time range, is included in the KML emplacement model ("Google Earth" file), so as to complete the story of granite emplacement on Connemara.

Gamma-Ray Spectrometric Data

The spatial distribution of radioelements (K, U and Th) in the Galway Batholith was investigated by Feely and Madden (1986; 1987). A calibrated Geometrics GR 410A differential four-channel portable gamma-ray spectrometer was used to analyze granite exposures. Five two-minute counts were taken on flat exposures to estimate bedrock assays of K wt.%, e (= equivalent) U ppm and eTh ppm (where 1 ppm eU= 1 ppm U and 1 ppm eTh= 1 ppm Th, both in radioactive equilibrium with gamma-emitting daughters). Lovborg (1984), Madden (1987) and Madden and Feely (1987) outlined the calibration procedures used for the Galway Batholith survey. 700 gamma-ray stations were established and include both onshore and offshore exposures (Figure 3). Poor exposure in the central block left unavoidable gaps in the coverage. Hand contoured maps showing the spatial distribution of the radioelements and the associated surface heat production (HP) were published by Feely and Madden (1987) and highlighted a notable decrease in radioelement abundances going from west to east across the NE trending Shannawona Fault Zone (SFZ). The SFZ and Barna Fault Zone (BFZ) on the west of Galway City represent major structural delineations in the granite batholith. The region in between the aforementioned faults is referred to as the Central Block. From gravity-modeling studies, Madden (1987) determined that the spatial extent of the Galway Granite batholith displays a thickening of the western (8-12km) and eastern (8-10km) ends, separated by a relatively thinner (4-6km) central block. This thinner central block corresponds to the section bounded by the SFZ and BFZ (Figure 2). Leake (1978) suggested an upthrow of several kilometers on the eastern side of the SFZ. Gravity modeling studies carried out by Madden (1987) support this assertion, proposing an upthrow of about 2 km, and an estimated thickness of 2-3 km for the CMG. The most radioelement rich granite however, the leucocratic Costelloe Murvey Granite (CMG), lies to the east of the SFZ. This granite is reported by Feely *et al.* (2003) to represent the final emplacement of granite in the batholith at approximately 380 Ma. Radioelement concentrations increase with petrological evolution throughout the batholith (Feely and Madden 1986). Radioelement determinations are lowest in the least evolved mafic granites of the batholith (central block) and increase through the Carna Granite and Errisbeg Townland Granite (ETG). K, U and Th concentrations are highest in the evolved Murvey granites, particularly in the CMG (Feely and Madden 1986). Heat flow anomaly modeling of the batholith predicted surface heat flow values of approximately 72-79 mWm^{-2}, with resultant temperature gradients of approximately 21-23ºC/km (Madden 1987).

Figure 3. Distribution of Spectrometer Survey Stations



Distribution of Spectrometer Survey Stations

Google Earth Science and KML

The unattributed claim that 80% of all information has a geographical component (Hart and Dolbear 2007) can only encourage the emergence of a geospatial web. The development of geo-browsers and 3D Earth viewers in recent years is evidence of how our inherent spatial awareness can be harnessed to provide improved modes of information retrieval and communication. The value of a geospatially-enabled Web to the geoscience community is immense. Geologists operate in a scientific realm that requires an appreciation of the 3D geometry of the Earth, as well as the temporal component associated with geological processes. The ability to access a spectrum of geological information for specific locations at a range of scales and perspectives represents a potential paradigm shift in accessing geological information. Geo-browsers such as Google Earth serve as excellent Earth observation applications and resources, providing free access to satellite imagery and 3D topographic data of the entire planet. Similar to GIS applications, 3D Earth viewers have become a standard feature on the desktops of geologists throughout the globe. Mike Goodchild of the University of California, Santa Barbara remarked, "Just as the PC democratized computing, so systems like Google Earth will democratize GIS" (Butler 2006a).

The use of Google Earth for scientific visualization has been widely documented in recent literature (Biever 2005; Lubick 2005; Brodersen 2006; Dunne and Sutton 2006; Gramling 2007). Lisle (2006) provides a comprehensive insight into the use of Google Earth as a geological visualization tool. Dunne and Sutton (2006) demonstrate how large-scale multi-beam imagery datasets can be integrated into Google Earth using a combination of KML and OpenGIS WMS (Web Map Service) technologies. Beck (2006), Allen (2007) and Patterson (2007) examine the application of Google Earth for student instruction and geoscience education. The potential of Google Earth for geoscientific visualization is notable from the emergence of dedicated geological conference sessions dedicated to the use of Google Earth and other 3D earth viewers. The use of Google Earth for scientific visualization outside of the Earth science domain is widely appreciated and equally well documented (see Boulos 2005; Duindam 2006; Stanger 2006; Butler 2006b).

A principal advantage of using Google Earth for geoscientific visualization is the ability to add customized geospatial content to the application using KML. KML is an Extensible Markup Language (XML) dialect (World Wide Web Consortium 2008). KML files can be created ‘internally’ using the Google Earth application, or ‘externally’ using any standard XML or text editor. KML files containing text, imagery and 3D models can be compressed to KMZ (zipped KML) files. 3D modelling software applications such as SketchUp™ and GIS software with KML export functionalities provide additional methods in generating content for Google Earth. This compression functionality allows multiple file-formats (e.g. KML, PNG, DAE) to be merged into one KMZ file, allowing for efficient distribution of KML content via email, Intranet, or served on the World Wide Web. In addition, KML files can be viewed in Google Maps™ in 2D.

Generation of the Geochemical Maps

The use of GIS for the geostatistical interpolation of radioelement data is well documented throughout scientific literature (Kemski *et al.* 2001; Rybach *et al.* 2002; Lech *et al.* 2003; Tourliere *et al.* 2003; Lima *et al.* 2005; Ruffell *et al.* 2006). The production of a smooth geostatistical map derived from irregularly spaced survey data involves the interpolation of the original data onto a mesh of values at regularly spaced intervals (IAEA 2003). Lech *et al.* (2003) employed an IDW interpolation gridding method to investigate variations in uranium abundances in granites. Rybach *et al.* (2002) examined the spatial distribution of radiation exposure of the population in Switzerland using GIS, based on data sources that included terrestrial gamma-ray spectrometry. Lima *et al.* (2005) compiled a series of radioactivity and U, Th and K geochemical maps and demonstrated a close relationship between the individual lithologies and radioelement concentrations. Other studies of radioelement concentrations in Ireland include the work of Hadley *et al.* (2000), who used gamma-ray spectrometry to study structural relations in the Dalradian rocks of Donegal, northwest Ireland.

Owing to the irregular spacing of the spectrometric data, an IDW interpolation technique was deemed a suitable interpolation method for this study. IDW interpolation estimates grid cell values by averaging the values of sample data points in the vicinity of each cell. The closer a point is to the centre of the cell being estimated, the more influence, or weight, it has in the averaging process. IDW interpolation is suited for geochemical mapping because it fits the source data accurately and preserves local anomalies in the interpolation grid (Robinson and Ayotte 2006). IDW interpolation, based on the method developed by Shepard (1968), is a widely used interpolation technique used by earth scientists (Ware *et al.* 1991). The resultant IDW grids were generated at a cell size of 50 m.

The raw survey data (Appendix 2, Madden, 1987) was digitized using optical character recognition (OCR) software, and georeferenced using MapInfo GIS software. The original dataset was tied to the Irish National Grid (ING) and all data processing was carried out in the ING coordinate system. The dataset comprises of measurements pertaining to radiogenic heat production throughout the batholith. Heat production values (A) were calculated using an equation adapted from that of Drury and Lewis (1983), using the relationship $A = (0.0963\ cU + 0.0264\ cTh + 0.0358\ cK)\rho$; where ρ is rock density in Mgm^{-3}, c denotes radioelement concentration in Wkg^{-1} and A = heat production in W/m^3.

Variations in the geochemistry within the individual granite bodies were investigated by applying geological boundary limits to the gridding process. A separate IDW interpolation process was carried out on each of the individual granite units of the Galway Batholith (Figure 2). Using a default MapInfo grid generation option, the boundary of each granite unit was used to clip each grid for that associated granite body. Processing each lithological unit independently prevented adjacent lithologies with distinctly different chemistries from influencing the final interpolation process. This method is reliant on there being an adequate density of survey points within each geological unit. The same IDW gridding parameters were used for all granite units, with the exception of the Lough Fadda Granite (Table 1). A smaller search radius was necessary for the Lough Fadda Granite, owing to the significantly smaller outcrop area of this granite body relative to all other granite units. The density of survey stations (Figure 3) is variable over the study area and this factor must be taken into consideration when interpreting the maps. Regions of low sample density generally correspond to areas of little or no exposure (mainly heathland and wetland). Areas lying outside of the search range of a survey station appear grey in the interpolated maps.

Table 1. IDW interpolation parameters used for radioelement maps.

	Cell size	Search Radius	Exponent
Lough Fadda Granite	0.05km	0.8km	2
All other granite units	0.05km	2.0km	2

The resultant maps provide an indication of the geochemistry for each specific lithological unit. The final geochemical raster grids were projected in the WGS84 reference system, in accordance with the coordinate system used in Google Earth, and formatted as a PNG image file, enabling transparency for regions outside of the study area.

A super-overlay is used to load the geochemical maps at different resolutions, depending on the zoom level. Owing to the distribution of the survey stations, a cell size of 50m is used. A zoom-level limit was placed on the geochemical KML files so as to avoid over-pixilation and loss of detail. When the viewer zooms in too closely, the map is no longer displayed. This is a standard feature in Google Maps.

Visualization of Geochemical Maps in Google Earth

Four maps were generated from the spectrometry assay data ("Google Earth" file). The geochemical maps are displayed in Google Earth using the <GroundOverlay> KML element. The set of maps are listed as features in the Places panel in the Google Earth sidebar. Users can switch between the various maps using radio button controls. The radio button function is configured in KML using the <ListStyle> tag. The <radioFolder> option, used within the <listItemType> tag allows only one item within a specific folder' to be activated at a time. The transparency of each map can be altered, allowing the maps to be interrogated in respect of the batholith geological bedrock map provided as an image overlay. When activated, the associated legend for each map is displayed on the left side of the 3D viewer using the <ScreenOverlay> KML tag.

Building the 4D Emplacement Models

The 4D schematic model of the emplacement of the Connemara granites employs the Google Earth time-slider control, available in Google Earth version 4 or greater. Spatial surface coverage of the granite bodies was extracted from Geological Survey of Ireland 1:100000 scale Sheet 10 (Long and McConnell 1995) and Sheet 14 (Pracht *et al.* 2005). A KML file for each granite body was generated using ArcGIS™ and Shape2Earth™ software, using the <PolyStyle> KML element. Each KML file was extruded by a value of 500 m and projected in WGS84 projection system, conformable with the projection system used in Google Earth. Extrusion of the polygons provides a discernible footprint of each granite body. The ages of emplacement are represented by units of years *before the Common Era* (BCE). BCE is the default abbreviation used in Google Earth. In an attempt to adhere to standard geological time notation, we configure the temporal models such that one Google Earth year represents one million years (e.g. 430 BCE ≈ 430 Ma). A KML file was generated for each of the 3D granite models. These KML files can be considered as the child files that are accessed from the parent KML file using the <Link> element, with each <Link> element nested within a KML <Folder> tag. As the parent of the <Link> element is the <NetworkLink> tag, the <href> (hypertext reference) is a KML file. The <href> can be a locally specified file or an remote URL (Google 2007). The example below shows the syntax used to activate the CMG model in the parent KML file.

```
<Folder>
    <name>Costelloe Murvey Granite</name>
    <Style>
        <ListStyle>
            <listItemType>radioFolder</listItemTyp
            <bgColor>00ffffff</bgColor>
        </ListStyle>
    </Style>
    <Folder>
        <name>Off</name>
        <visibility>0</visibility>
    </Folder>
    <NetworkLink>
        <name>On</name>
        <Snippet maxLines="0"></Snippet>
        <Link>
            <href>cmg_granite.kml</href>
        </Link>
    </NetworkLink>
```

```
</Folder>
```

The granite emplacement events are configured in each KML file using the <TimeSpan> tag, with the KML elements <begin> and <end> used to define the dates of emplacement for each of the various Connemara granite units.

```
<TimeSpan>
    <begin>-380</begin>
    <end>-360</end>
</TimeSpan>
```

To allow the animation to run for a brief introductory time period before the first granite body is emplaced, a <TimeSpan> tag is used within a <ScreenOverlay> tag. This feature enables the animation to commence at 488 Ma, whereby a legend is displayed in the viewer, prior to the emplacement of the Oughterard Granite at 463 Ma, and the subsequent emplacement events thereafter.

Discussion

This study demonstrates a methodology for displaying multi-dimensional geological data in Google Earth. The animation time range of the granite emplacement model is configured to commence at 488 Ma (Lower Ordovician), and to end at 360 Ma (Late Devonian). These dates were chosen to enable the animation to have a time lapse prior to and following to emplacement of the models. It is herein acknowledged that the display of monthly information on the time-slider is unnecessary, however this appears to be a default component of the Google Earth time-slider. Much of the study area is represented by relatively low-resolution imagery and DTM data, this is not deemed to be a significant issue for this kilometric scale study.

Emplacement Models

The 3D granite emplacement models demonstrate the intrusive episodes of late-Caledonian granites in Connemara during time period of approximately 40 Ma. The Galway Granite batholith is considered by the Leake (1978) to be a stitching pluton that postdates the Skird Rocks Fault (Figure 2). Leake (1978) suggests that Skird Rocks Fault is a splay off the Southern Uplands Fault and a major influence in the siting of the pluton. The emplacement model demonstrates how the near east-west trending major axis of the batholith is almost parallel to the Skird Rocks Fault and Southern Uplands Fault.

3D KML models representing the separate granite units are used to enhance the visual footprint of the units, and to augment the ‘appearance’ of each of the units in relation to their respective emplacement age. The 3D models are not representative of the space form of the granite plutons. The purpose of these visualizations is to demonstrate the geochronology of the emplacement of the Connemara granites. It is herein argued that this method of presenting dynamic visualizations conforms with the principles of congruence and apprehension (Tversky *et al.* 2002; Dutrow 2007). To satisfy the principle of apprehension, animations must be slow and clear enough for the viewer to perceive movement, change, and any associated temporal components, and to understand changes in the sequence of events. Viewers can control the speed of the Google Earth time-slider, thus maintaining control over the animation speed. The use of interactive animations is known to facilitate learning (Schnotz *et al.* 1999; Dutrow 2007). The use of coloured 3D volumetric models to represent the granite units is intended to simplify visualization of a complex system of plutonic emplacement.

Fundamental to the success of all geological visualizations is the requirement for the graphical information to be comprehensible by the observer. Tversky *et al.* (2002) suggest that effective graphics conform to the congruence principle when the content and format of the graphic corresponds to the content and format of the concepts being conveyed. Through the use of volumetric models to represent granite bodies, instead of image overlays or 2D polygons, the concept of a 3D volume of granitic rock is conveyed. The concept of emplacement is presented via the time-slider, giving the viewer the impression of a plutonic mass appearing, or being emplaced. It is the objective of this study to demonstrate the application of Google Earth for communicating 3D geoscience visualizations and the incorporation of a fourth (temporal) dimension to enhance the communicative effectiveness.

Gravity modelling of the Galway Granite batholith indicates a large volume of low-density material extending to maximum crustal depths of 10-12km (Madden 1987). However, the vertical extrusion of the KML granite emplacement models does not reflect the measured thicknesses of the individual granite bodies. Madden (1987) modelled the thickness of the eastern, central and western regions of batholith (Figure 4 and Table 2) using two different density (ρ) contrast values (ρ contrast = [ρ unknown body] – [ρ country rock]). A density value of 2.74 Mgm^{-3} was used for the country rock. Using a density contrast value of -0.05 Mgm^{-3} for the Costelloe-Murvey Granite, an estimated thickness of 2-3km is assumed (Madden 1987).

Figure 4. Cross-section of the Galway Granite Batholith showing thickness of the western, central and eastern batholith blocks (after Madden 1987).

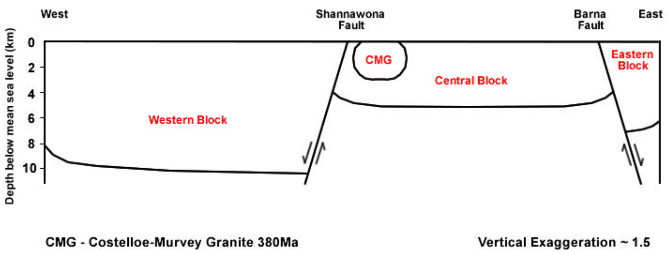


Table 2. Estimated thicknesses of the western, central and eastern batholith blocks as determined from gravity modelling (after Madden 1987)

	Western Block	Central Block	Eastern Block
Model One: ρ contrast = -0.090 Mgm^{-3}	8-12km	~6km	8-10km
Model Two: ρ contrast = -0.11 Mgm^{-3}	6-10km	~5km	6-8km

The modelled thicknesses of the granite bodies reflect the depth to the base of the units. Assigning the measured thickness values to the KML models would render the thicker units (western and eastern) to stand proud of the central unit in Google Earth, and effectively invert the batholith. This 3D representation would not reflect the space-form structure of the batholith and would not conform to the principle of congruence (see Tversky *et al.* 2002). The principle of congruence, when applied to animated visualizations, demands that graphical representations of physical systems should correspond to the true structure of the physical system in reality.

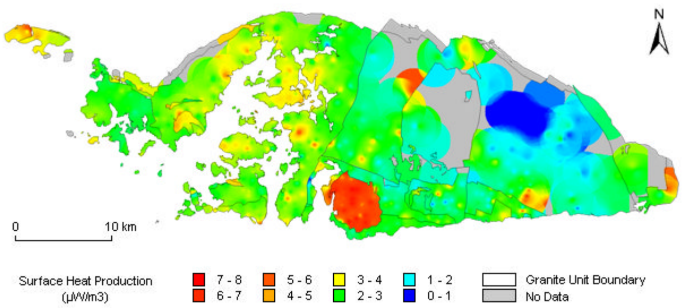
As we have discussed, the age of emplacement of the Inish Granite and Letterfrack Granite is uncertain, and the assumed date of emplacement is pre-410 Ma (Friedrich *et al.* 1999). The four satellite plutons (Omey, Roundstone, Letterfrack and Inish) are attributed an emplacement date of 420 Ma. To demonstrate the emplacement of the central block prior to uplift (approximately 390-385 Ma), a semi-transparent layer is used to represent the central block granite roof. The semi-transparent layer, corresponding to the ETG, is coloured the same as the associated ETG models. At the estimated time of uplift on the central block, this semi-transparent layer disappears. The remaining surface signature of the granite units corresponds to the most recent map of the Galway Granite batholith (Feely *et al.* 2006). The generation of a time-based animation of the emplacement events of the Connemara granites emphasizes the potential uses of Google Earth for schematic geochronological visualizations of complex regional geological systems.

Gamma-Ray Spectrometry

This study represents the first correlation of the gamma-ray spectrometry survey data with the recently updated map of the Galway Granite batholith (Pracht *et al.* 2005). The lithologies of the Spiddal Granite in Feely and Madden (1987) have since been remapped and differentiated into the Knock Granite, Lough Lurgan Granite, Shannapheasteen Granite, Lough Fadda Granite and the MMZ (Pracht *et al.* 2005; Feely *et al.* 2006). Through the interpolation of the spectrometry data, controlled by lithological boundaries, the revised series of geochemical maps can be interrogated relative to the currently accepted geology of the Galway Batholith. The regional variations in K, U, Th and HP associated with the Galway Granite support the aforementioned work of Feely and Madden (1987) in showing the geochemical discontinuity across the SFZ.

In particular, the contrast in HP across the SFZ is evident (Figure 5) and in the KMZ maps presented. West of the SFZ, HP values are predominantly in the range of 3-5 W/m^3, while east of the fault values tend to fall mainly in the 1-3 W/m^3 range. This contrast appears to exist across the BFZ also, with higher HP values to the east of the fault. However, due to the low number of survey stations east of the BFZ, this contrast may not be as accurate as in the SFZ region. The Murvey Granite at Roundstone, on at the very western end of the Galway Batholith shows high HP values of 4-6 W/m^3. The CMG displays the highest HP values (5-7.83 W/m^3) measured on the batholith. Two anomalies of HP values exceeding 6 W/m^3 were calculated from radioelement data recorded in the central block (Figure 4). Both values were recorded in aplite veins at Spiddal (6.55 W/m^3) and 10km northeast of the CMG region (6.27 W/m^3). Feely and Madden (1986, Table 3) presented mean HP values for a seven different granite types in Ireland, Britain and New Hampshire, ranging from 1.83 W/m^3 to 8.03 W/m^3. The CMG (6.41 W/m^3) was second only to the Conway Granite (8.03 W/m^3) of New Hampshire (Fehn *et al.* 1978) and can be considered as a high heat production granite.

Figure 5. Surface Heat Production map of Galway Granite.



Surface Heat Production map of Galway Granite.

Conclusion

The presentation of 3D and 4D maps in KML serve as an informative resource for visualizing the inter-relationships of late-Caledonian granite geology, geochemistry and geochronology in Connemara, western Ireland. The 3D emplacement maps of the Connemara granites demonstrate the various episodes in the siting of the granite plutons. The ~390 Ma faulting (i.e. Barna Fault and Shannawona Fault) can be seen to coincide with the ‘unroofing’ of the Central Block causing the relative uplift of the Megacrystic Granite, Lough Lurgan Granite and MMZ Granite (Madden 1987). The NW-SE trending long axis of the batholith clearly lies across the E-W trend of the Skird Rocks Fault which is a splay of the regional scale Southern Uplands Fault. The presence of CMG, emplaced at 380 Ma, is reflected in the geochemical maps. The leucocratic CMG contains high radioelement abundances and HP values relative to the other granites.

The methods of 4D schematic visualization in Google Earth presented here demonstrate how visualizations of multi-dimensional geological information can be presented to the widest possible audience. The visualizations presented enable users to gain an insight into the emplacement events of the Connemara granites, and their distribution of radioelements. Furthermore, it is intended that this study will serve as a resource for student instruction on 3D and 4D geological visualizations of granite emplacement coupled with geochemistry and geochronology.

Acknowledgements

The authors would like to acknowledge the work of J.S. Madden in carrying out the gamma-ray spectrometry survey of the Galway Granite batholith. A further acknowledgement goes to Ms. Marie Mannion, Heritage Officer, Galway County Council. RH would like to acknowledge support for this work from the Irish Research Council for Science, Engineering and Technology.

References

Allen, T. R. (2007). "Digital Terrain Visualization and Virtual Globes for Teaching Geomorphology." Journal of Geography 106(6): 253-266. 10.1080/00221340701863766

Baxter, S. and M. Feely (2002). "Magma mixing and mingling textures in granitoids: examples from the Galway Granite, Ireland." Mineralogy and Petrology 76: 63-74. 10.1007/s007100200032

Baxter, S., N. T. Graham, et al. (2005). "A microstructural and fabric study of the Galway Granite, Connemara, western Ireland." Geological Magazine 142(1): 81-95. 10.1017/S0016756804000378

Beck, A. (2006). "Google Earth and World Wind: remote sensing for the masses?" Antiquity 80(308).

Biever, C. (2005). "Will Google help save the planet?" New Scientist 187(2512): 28-29.

Boulos, M. N. K. (2005). "Web GIS in practice III: creating a simple interactive map of England's Strategic Health Authorities using Google Maps API, Google Earth KML, and MSN Virtual Earth Map Control." International Journal of Health Geographics 4: 22-29. 10.1186/1476-072X-4-22

Brodersen, L. (2006). Free is Good: Is Google Earth 'The End' or 'A Beginning'. GeoConnexion. 5.

Butler, D. (2006a). Virtual globes: The web-wide world. Nature. D. Butler. 439: 776-778.

Butler, D. (2006b). "Avian flu maps in Google Earth." Retrieved 29 June, 2007, from http://declanbutler.info/blog/?p=58.

Crowley, Q. and M. Feely (1997). "New perspectives on the order and style of granite emplacement in the Galway Batholith, western Ireland." Geological Magazine 134: 539-548. 10.1017/S0016756897007218

Drury, M. J. and T. J. Lewis (1983). "Water movement within Lac du Bonnet Batholith as revealed by detailed thermal studies of three closely-spaced boreholes." Tectonophysics 95: 337-351. 10.1016/0040-1951(83)90077-X

Duindam, A. J. (2006). "Google Earth: What GI Professionals Can Gain From It." GIM International 20(4).

Dunne, D. and G. Sutton (2006). "3D Web-mapping: Integrating Marine Data into Google Earth." Hydro International 10(7): 27-29.

Dutrow, B. L. (2007). "Visual communication: Do you see what I see?" Elements 3(2): 119-126. 10.2113/gselements.3.2.119

El Desouky, M., M. Feely, et al. (1996). "Diorite-granite magma mixing along the axis of the Galway Granite batholith, Ireland." Journal of the Geological Society, London 153: 361-374. 10.1144/gsjgs.153.3.0361

Feely, M., D. Coleman, et al. (2003). "U-Pb zircon geochronology of the Galway Granite, Connemara, Ireland: implications for the timing of late Caledonian tectonic and magmatic events and for correlations with Acadian plutonism in New England." Atlantic Geology 39(2): 175-184.

Feely, M., B. E. Leake, et al. (2006). A Geological Guide to the Granites of the Galway Batholith, Connemara, western Ireland. Dublin, Geological Survey of Ireland.

Feely, M. and J. S. Madden (1986). A quantitative regional gamma-ray survey on the Galway Granite, western Ireland. Geology and Genesis of Mineral Deposits in Ireland. C. J. Andrew, R. W. A. Crowe, S. Finlay, W. M. Pen-nell and J. Pyne. Dublin, Irish Association for Economic Geology: 195 - 200.

Feely, M. and J. S. Madden (1987). "The spatial distribution of K, U, Th and surface heat production in the Galway Granite, Connemara, western Ireland." Irish Journal of Earth Sciences 8(2): 155-164.

Feely, M. and J. S. Madden (1988). "Trace element variation in the leucogranites within the Main Galway Granite, Ireland." Mineral Magazine 52: 139-146. 10.1180/minmag.1988.052.365.01

Feely, M., E. McCabe, et al. (1989). "U-, Th- and REE-bearing accessory minerals in a high heat production leucogranite within the Galway Granite, western Ireland." Transactions of the Institute of Mining and Metallurgy 98, B27–B32.

Feely, M., D. Selby, et al. (2007). "Re-Os geochronology and fluid inclusion microthermometry of molybdenite mineralisation in the late-Caledonian Omey Granite, western Ireland." Applied Earth Science (Trans. Inst. Min. Metall. B) 116(3): 143-149.

Fehn, U., L. M. Cathles, et al. (1978). "Hydrothermal Convection and Uranium Deposits in Abnormally Radioactive Plutons." Economic Geology 73(8): 1556-1566. 10.2113/gsecongeo.73.8.1556

Friedrich, A. M., K. V. Hodges, et al. (1999). "Geochronological constraints on the magmatic, metamorphic and thermal evolution of the Connemara Caledonides, western Ireland " Journal of the Geological Society, London 156(6): 1217-1230. 10.1144/gsjgs.156.6.1217

Google. (2007). "KML 2.1 Reference." Retrieved 03/01, 2008, from http://code.google.com/apis/kml/documentation/kml_tags_21.html.

Graham, N. T., M. Feely, et al. (2000). "Plagioclase-rich microgranular inclusions from the late-Caledonian Galway Granite, Connemara, Ireland " Mineral Magazine 64: 113-120. 10.1180/002646100549030

Gramling, C. (2007). "Google Planet: With Virtual Globes, Earth Scientists See a New World." Geotimes 52(2): 38-39.

Hadley, M. J., A. Ruffell, et al. (2000). "Gamma-ray spectroscopy in structural correlations; an example from the Neoproterozoic Dalradian succession of Donegal (NW Ireland)." Geological Magazine 137(3): 319-333. 10.1017/S0016756800003976

Hart, G. and C. Dolbear (2007). Whats So Special about Spatial? The Geospatial Web: How Geobrowsers, Social Software and the Web 2.0 are Shaping the Network Society. A. Scharl and K. Tochtermann. London, Springer: 295

IAEA (2003). Guidelines for radioelement mapping using gamma-ray spectrometry data. Vienna, IAEA-TECDOC-1363, International Atomic Energy Agency.

Kemski, J., A. Siehl, et al. (2001). "Mapping the geogenic radon potential in Germany." The Science of The Total Environment 272(1-3): 217-230. 10.1016/S0048-9697(01)00696-9

Leake, B. E. (1978). "Granite emplacement: the granites of Ireland and their origin." In Crustal Evolution in Northwest Britain and Adjacent Regions (eds D. R. Bowes and B. E. Leake) Geological Journal, Special Issue 10(Liverpool: Seel House Press): 221-248.

Leake, B. E. (1989). "The metagabbros, orthogneisses and paragneisses of the Connemara complex, western Ireland." Journal of the Geological Society, London 146(4): 575-596. 10.1144/gsjgs.146.4.0575

Leake, B. E. (2006). "Mechanism of emplacement and crystallisation history of the northern margin and centre of the Galway Granite, western Ireland." Transactions of the Royal Society of Edinburgh: Earth Sciences 97(1): 1-23. 10.1017/S0263593300001371

Leake, B. E. and P. W. G. Tanner (1994). The geology of the Dalradian and associated rocks of Connemara, western Ireland.

Lech, M. E., O. L. Raymond, et al. (2003). "Potential applications in baseline geochemical data integration: a report of findings from a pilot study." Geoscience Australia Record 2003/008 Retrieved 03/01, 2008, from http://www.ga.gov.au/image_cache/GA2650.pdf.

Lima, A., S. Albanese, et al. (2005). "Geochemical baselines for the radioelements K, U, and Th in the Campania region, Italy: a comparison of stream-sediment geochemistry and gamma-ray surveys." Applied Geochemistry 20(3): 611-625. 10.1016/j.apgeochem.2004.09.017

Lisle, R. J. (2006). "Google Earth: A New Geological Resource." Geology Today 22(1): 29-32. 10.1111/j.1365-2451.2006.00546.x

Long, C. B. and B. McConnell (1995). Geology of Connemarra and South Mayo - Sheet 10: Solid Bedrock Geology 1:100,000 map series. Dublin, Geological Survey of Ireland.

Lovborg, L. (1984). The calibration of portable and airborne gamma-ray spectrometers - theory, problems, and facilities. Riso National Laboratory, DK-4000 Roskilde, Denmark, Report RisoM-2456: 207.

Lubick, N. (2005). "Spinning around the globe online." Geotimes 50(12): 60.

Madden, J. S. (1987). Gamma-ray spectrometric studies of the main Galway Granite, Connemara, west of Ireland. Unpublished PhD thesis, National University of Ireland, Galway.

Max, M., P. Ryan, et al. (1983). "A magnetic deep structural geology interpretation of Ireland." Tectonics 2: 431-451. 10.1029/TC002i005p00431

McKie, D. and K. Burke (1955). "The geology of the islands of south Connemara." Geological Magazine 93: 487-498. 10.1017/S0016756800064669

Murphy, T. (1952). "Measurements of gravity in Ireland: Gravity survey of Central Ireland." Dublin Institute for Advanced Studies, Geophysical Memoirs No. 2 Part 3: 31pp.

Patterson, T. C. (2007). "Google Earth as a (Not Just) Geography Education Tool." Journal of Geography 106(4): 145-152. 10.1080/00221340701678032

Pidgeon, T. T. (1969). "Zircon U-Pb ages from the Galway Granite and the Dalradian, Connemara, Ireland." Scottish Journal of Geology 5: 357-392.

Pracht, M., A. Lees, et al. (2005). Geology of Galway Bay: A geological description to accompany the Bedrock Geology 1:100,000 Scale Map Series, Sheet 14, Galway Bay. Dublin, Geology Survey of Ireland.

Robinson, J. G. R. and J. D. Ayotte (2006). "The influence of geology and land use on arsenic in stream sediments and ground waters in New England, USA." Applied Geochemistry 21(9): 1482-1497. 10.1016/j.apgeochem.2006.05.004

Ruffell, A., J. M. McKinley, et al. (2006). "Th/K and Th/U Ratios from Spectral Gamma-Ray Surveys Improve the Mapped Definition of Subsurface Structures." Journal of Environmental & Engineering Geophysics 11: 53-61. 10.2113/JEEG11.1.53

Rybach, L., D. Bachler, et al. (2002). "Radiation doses of Swiss population from external sources." Journal of Environmental Radioactivity 62(3): 277-286. 10.1016/S0265-931X(01)00169-2

Schnotz, W., J. Böckheler, et al. (1999). "Individual and co-operative learning with interactive animated pictures." European Journal of Psychology of Education 14: 245-265.

Selby, D., R. A. Creaser, et al. (2004). "Accurate Re-Os molybdenite dates from the Galway Granite, Ireland. A critical comment to: Disturbance of the Re-Os chronometer of molybdenites from the late-Caledonian Galway Granite, Ireland, by hydrothermal fluid circulation." Geochemical Journal 35: 29-35.

Shepard, D. (1968). A two-dimensional interpolation function for irregularly-spaced data Proceedings of the 1968 23rd ACM National Conference, p.517-524, August 27-29, 1968.

Stanger, N. (2006). The view from the Chathams: Geovisualisation of Web Site hits using Google Earth. 18th Annual Colloquium of the Spatial Information Research Centre (SIRC 2006: Interactions and Spatial Processes), Dunedin, New Zealand, University of Otago.

Tourliere, B., J. Perrin, et al. (2003). "Use of airborne gamma-ray spectrometry for kaolin exploration." Journal of Applied Geophysics 53(2-3): 91-102. 10.1016/S0926-9851(03)00040-5

Townend, R. (1966). "The geology of some granite plutons from Western Connemara, Co. Galway." Proceedings of the Royal Irish Academy 65(B): 157-202.

Tversky, B., J. Morrison, et al. (2002). "Animation: Can It Facilitate?" International Journal of Human Computer Studies 57: 247-262. 10.1006/ijhc.2002.1017

Ware, C., W. Knight, et al. (1991). "Memory intensive algorithms for multibeam bathymetry data." Computers and Geosciences 17(7): 985-993. 10.1016/0098-3004(91)90093-S

Whitworth, M. P. and M. Feely (1994). "The compositional range of magmatic Mn-garnets in the Galway Granite, Connemara, Ireland." Mineralogical Magazine 58(1): 163-168. 10.1180/minmag.1994.058.390.16

Williams, D. M., H. A. Armstrong, et al. (1988). "The age of the South Connemara Group, Ireland, and its relationship to the Southern Uplands Zone of Scotland and Ireland." Scottish Journal of Geology 24: 279-287.

World Wide Web Consortium. (2008). "Extensible Markup Language (XML)." Retrieved 03/08, 2008, from http://www.w3.org/XML/.