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# GROUNDWATER DISCHARGE MAPPING BY THERMAL INFRA-RED IMAGERY.

by

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THERMAL INFRA-RED IMAGERY.


ABSTRACT

An area around Altnabreac in northern Scotland has been studied as part of the UK programme of research into the feasibility of disposal of radioactive waste into geological formations. An essential pre-requisite to being able to predict the behaviour, migratory pathways and travel times of radionuclides emanating from a waste repository is an understanding of the regional and near surface groundwater flow systems and groundwater geochemical evolution. The groundwater system at depth has been studied by means of boreholes but an understanding of the shallow groundwater flow, and its interaction with groundwater upwelling from depth, can be gained from studies of the spatial distribution and geochemistry of surface springs and discharges. A survey was carried out using the thermal infra-red linescan technique with the objective of locating all significant spring discharges over the study area.

The terrain around Altnabreac is largely covered by superficial deposits which overlie weathered granite. The survey was carried out from a height of 275m at a spatial resolution of about 0.5m. About 280 line Km were covered but allowing for overlap between adjacent flight lines and some repeat coverage, the actual area surveyed was 68 sq Km.

The most striking aspect of the results is the wide distribution of groundwater discharges in the Altnabreac area. An analysis of the data identified three general categories of spring and many of these springs were subsequently visited for verification and to allow samples to be collected for chemical analysis. The results from this survey indicates that the groundwater table is strongly influenced by local topography and that the majority of the spring discharges represent near surface recent groundwaters circulating within the superficial deposits and weathered granite.

## 1. INTRODUCTION

The area around Altnabreac in northern Scotland, has been studied in some detail as part of the programme of research into the feasibility of disposal of radioactive waste into geological formations. An essential prerequisite to being able to predict the behaviour, migratory pathways and travel times of radionuclides emanating from a radioactive waste repository is an understanding of the regional and near surface groundwater flow system and groundwater geochemical evolution. For this reason a major component of the study has dealt with the hydrogeology and hydrogeochemistry of the area.

The groundwater system at depth can be studied by means of boreholes. At Altnabreac a series of three deep and twenty four shallow boreholes were drilled (Lintern and Raines, 1980). These have been tested for their hydrogeological characteristics (Holmes, 1981; Soil Mechanics, 1980) and groundwater samples have been collected for geochemical analysis (Kay and Bath, 1982).

An understanding of shallow groundwater flow, and its interaction with groundwater upwelling from depth, can be gained from studies of the spatial distribution and geochemistry of surface springs and discharges. In an area such as Altnabreac, where there is extensive peat cover and a relatively high annual rainfall, the ground surface is frequently boggy with areas of standing water forming pools called dubh lochs. Also, there is an extensive surface run-off system of streams and rivers.

On a visual inspection alone, it is not possible to distinguish between groundwater discharges and surface water run off. Groundwater, however, generally exhibits a fairly narrow temperature range throughout the year relative to a much wider surface water temperature range. Therefore, at certain times of the year a temperature contrast will exist which can be utilized to detect the groundwater discharges. A ground survey using conventional thermometers could achieve this over very small areas, but over the larger areas of almost permanently wet open country around Altnabreac, it would be extremely manpower intensive and, furthermore, almost impossible to cover the whole area at the required level of detail. An airborne thermal infra-red linescan survey from low flying aircraft can, on the other hand, cover large areas very rapidly.

Such a survey was carried out during the early Spring in both 1981 and 1982 with the objective of locating all significant spring discharges over the study area.

## 2. PRINCIPALS OF THERMAL INFRA-RED LINESCAN IMAGERY

The spectrum of electromagnetic radiations emanating from the earths' surface includes a reflected solar component and a self-emitted component. Reflected radiations are predominantly in the visible and near infra-red wave bands (0.4 to 3.0$\mu$m) and can be recorded onto photographic film to produce conventional black and white, colour or false colour imagery. Self emitted radiations extend from about 4.0$\mu$m into the far infra-red and micro wave bands with a maximum intensity at 9.6$\mu$m.

Thermal imagery is concerned with the middle infra-red but because of absorption by the atmosphere over certain wave bands, measurements are usually confined to the 8 to 14$\mu$m region where the radiation is almost entirely self emitted.

The energy emitted by the earths surface is a function of a number of factors, but the two most important are emissivity and temperature. For surfaces having a relatively constant emissivity factor, such as water, any variations in the intensity of radiated energy will be related to variations in the surface temperature, hence the name thermal infra-red.

Because of the lack of suitable emulsions sensitive to the thermal infra-red wavebands, conventional photographic equipment cannot be used and special detectors have been developed. The infra-red sensing element of the detector is a solid state device which converts the perceived energy into an electrical signal. A continuously rotating mirror scans the ground surface and directs the emitted radiation onto the sensing element via an optical focussing system (Figure 1). The electrical signal generated by the sensor is amplified and stored on magnetic tape for subsequent data processing.

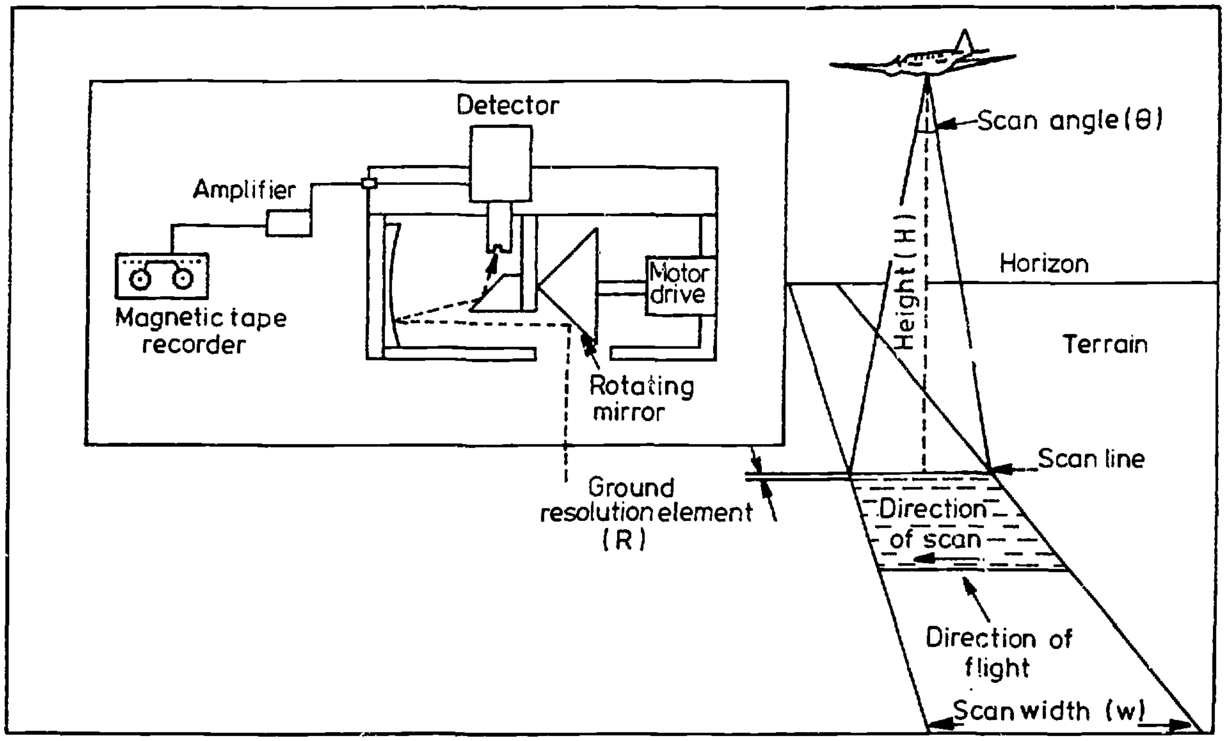


Fig. 1. Simplified diagram of an airborne thermal infra-red scanning system.

The scanning axis of the rotating mirror is mounted such that a ground image is built up by a combination of the rapid lateral scanning motion of the detector and the forward motion of the aircraft, to produce a continuous record of the overflown target. To overcome image distortion due to aircraft roll or cross wind crabbing, the detector head is usually fitted with stabalising compensators.

The spatial resolution and ground area coverage on the image are governed by the instantaneous field of view ( $\phi$ ) and scan angle ( $\theta$ ) of the equipment, and by the height at which the aircraft is flown ( H ). The equipment used for the Altnabreac surveys was a Daedalus DS 1230 scanner for which $\phi$ os 0.1 degrees and $\theta$ is 77.3 degrees. These parameters result in a width of scan in the direction of flight ( or ground resolution element, R) and the width of scan on the ground (W) being directly related to flying height such that:-

$$R = 0.0017\ H$$

and

$$W = 1.60\ H$$

At the data processing stage the analogue electrical signal, recorded on the magnetic tape, can be digitized to a format compatible with computer analysis. The data across each scan width is divided into 696 discrete units such that the ground resolution (P) of these units is:-

$$P = 0.0023\ H$$

Therefore, a digitized image will be made up from a matrix of discrete elements each having the ground resolution dimensions of R x P. These picture elements are called pixels.

To overcome some of the uncertainties connected with the flying height, a preliminary trial survey was undertaken at heights of 200 m, 275 m, 350 m, 450 m and 600 m. The area chosen for the trial was known to contain several springs, some of which have dimensions of 0.3 m sq. or less. At the higher altitudes it was found that the pixel size would be significantly larger than some of the springs. The effect of this is to produce a lower average recorded temperature because the pixel will encompass the small higher temperature anomaly along with its lower temperature immediate surroundings. The true temperature of the anomaly will only be recorded if the central uniform temperature zone of the anomaly is entirely covered by one or more pixels. These factors tend to encourage low altitude surveys. On the other hand, higher altitude surveys increase the ground coverage for each pass and therefore enable larger areas to be surveyed more quickly. Following the trial survey it was considered the optimum flying height for the conditions prevailing in the Altnabreac area was 275 m. This would result in a ground scan width of 440 m and pixel dimensions of 0.47 m by 0.63 m. It was therefore decided to adopt a flying height of 275 m for all subsequent surveys.

The Daedalus equipment is capable of resolving temperatures of 0.2°C over a range from -10°C to +40°C. In addition, to enable calibration and data quantification, two black body reference temperatures are recorded at either end of each scan line. This internal temperature calibration system minimises the need to carry out comprehensive ground control exercises at the time of the survey.

Detection of a groundwater spring discharge on the basis of its temperature will depend upon the temperature contrast between the spring and its surroundings. Groundwater tends to exhibit a relatively narrow temperature range throughout the year. In northern Scotland for example, the range is from about 5°C in the winter to about 8°C in the summer. By contrast, surface waters will vary, according to weather conditions, from below freezing in winter to above 15°C in the summer. The surface waters will gradually warm up during the summer months and reach their maximum temperatures in the early autumn. Converseley, they will gradually cool down during the winter months and reach their minimum temperatures in the early spring.

Natural recharge of the groundwater system predominates during the winter months. Groundwater levels are at their maximum during late winter or early spring and at their minimum during the early autumn. The maximum volumes being discharged by groundwater springs will, therefore, coincide with the early spring (February/March) peak temperature contrast period.

The best quantitative results are obtained during the hours of darkness. This not only avoids any residual reflected radiation component but also minimizes the effects of solar heating. Low level night flying introduces navigational problems however, and also it is necessary to allow sufficient time after sunset for heat stored by surface materials during the day to dissipate. Therefore, the optimum time for carrying out a survey is a limited pre-dawn period during February/March when there is no rain or snow, clear visibility and ground temperatures are at or below freezing.

Thermal infra-red imagery has been used for a variety of purposes, including groundwater resource evaluation studies; monitoring heat waste discharges into rivers; and heat loss surveys from buildings for energy conservation purposes. The majority of groundwater studies have been concerned with detecting springs discharging into coastal waters, lakes or streams.

Brereton and Downing (1975) used the technique to locate spring discharges from the Chalk aquifer onto coastal foreshores and also to estimate the application of the technique for the location of spring discharges into small streams. One of the conclusions to be drawn from their work is that for springs emanating into surface waters, the mixing ratio is all important in determining whether or not the spring will be detected. Springs which form the stream headwaters, or discharge from the banks of a stream or river, will be detected by virtue of their own thermal anomaly. However, when a spring discharges beneath the surface of a stream, river, lake or the sea then the spring will only be detected if the remnant thermal anomaly, after mixing, is within the temperature resolution limits of the detector. That is, if a high-flow point-source discharge of high temperature contrast emanates into a low-flow or shallow surface water body then the thermal anomaly after mixing should be readily detected. If, on the other hand, a low-flow spring emanates into a high-flow or deep surface water body, then rapid mixing will take place and the thermal anomaly at the water surface may be too small to be detected.

## 3. THE ALTNABREAC AREA

In sedimentary aquifer studies groundwater discharge points can, to some degree, be predicted from a knowledge of rock outcrops, hydraulic head differences and relative permeabilities. At the beginning of this study, however, little was known about groundwater circulation patterns in the fractured crystalline rocks at Altnabreac. Although the positions of a few springs were available from local knowledge, it was not known how representative these were; whether the groundwater discharges could be categorised to indicate different groundwater regimes; or whether discharge positions could give an indication of groundwater upwelling from depth along preferential flow paths such as fault lines.

The terrain around Altnabreac is largely covered by peat which is underlain by glacial deposits which in turn overlies the weathered bedrock (Lintern and Storey 1980). The weathering profile extends to about 40 m. The geology of the Altnabreac area (McCourt, 1980; Lintern and Storey, 1980) consists of a large easterly dipping granite sheet, the Strath Halladale Granite, which was emplaced within Moine metasediments during the final stages of deformation.

Topographically, the area is mostly gently rolling to flat country betwen 100 m and 200 m above ordnance datum, with broad flat valleys. In the southern part, however, the rivers are more deeply incised, the slopes are steeper and more abrupt, and the relief rises to over 300 m.

Glendining (1980) carried out a hydrogeological assessment of the area and identified the most important surface water catchment areas. The lochs, which often represent the sources of small streams, are generally less than a few metres deep and usually have beds of coarse sand and boulders. A characteristic feature of the area is the dubh locks. These are small shallow pools a few metres across with steep sides and peat bottoms which occur in concentrations on flat plateau-like stretches of boggy ground. An interesting aspect of the dubh locks is that the water levels in adjacent lochs only a few metres apart are frequently at different datum levels.

Borehole water level measurements carried out by Glendining (1980) were analysed in terms of flow nets, from which it was possible to define the regions most likely to reflect high hydraulic conductivity. These tended to be in the river and stream valleys. In general, the surface water and groundwater systems were thought to be in hydraulic continuity and it was evident that the water table (defined by the borehole water levels) is often very close to the topographic surface, and in many places coincident with it.

## 4. THE SURVEY

The thermal infra-red survey of the Altnabreac area was began on 4 March 1981 at 07.30 hours, after overnight sub-zero temperatures, and continued for 2 hours. By this time hazy sunshine was beginning to cause ground warming. Surveying was continued the following morning but by the third day a general rise in atmospheric temperatures resulted in the survey being called off for the remainder of that year. The survey was resumed on 16 February 1982 after a period of over two weeks waiting for suitable weather conditions. By 18 February weather conditions had begun to deteriorate and it was again necessary to bring the survey to a premature completion.

Between the 1981 and 1982 surveys about 280 line Km of coverage was achieved. This represents a ground area of about 123 Sq. Km. but because of overlap between adjacent flight lines, the area covered during the two periods was about 90 Sq. Km. However, due to repeat coverage of some parts, the actual survey area was 68 Sq. Km. The original intention had been to survey a larger area, but this was prevented by the limited operational "windows" during which conditions were suitable.

## 5. DATA ANALYSIS AND INTERPRETATION

The thermal anomalies perceived by the Daedalus infra-red scanner are recorded onto magnetic tape. The tape is subsequently played back via a fibre optic light beam system which produces a photographic record for preliminary analysis. This imagery is referred to as "quick-look" because it is not geometrically corrected and the scales along and across the direction of flight are not accurate.

It was evident that the interpretation of some of the data collected towards the end of each mornings surveying was somewhat ambiguous. This was due to the rising sun heating south facing slopes and peat banks leading to difficulty in being able to judge whether the resultant thermal anomalies are due to groundwater discharge or solar heating. Despite such ambiguities on some of the survey lines, it was generally fairly easy to identify spring discharges by virtue of their strong thermal contrast.

One aspect of spring identification which became apparent from the photographic records was springs which emanate into the beds of streams and rivers. It was evident that when a spring exhibiting a large thermal contrast discharged into a small stream, then the overall temperature of the stream was raised for some considerable distance downstream of the discharge point. This led to difficulty in being able to identify further groundwater discharge points downstream of the first spring. Similarly, springs discharging into the bed of the larger rivers were difficult to unambiguously identify due to the rapid mixing effect discussed previously. It was anticipated that some of these difficulties would be overcome by digital enhancement.

Where thermal anomalies are particularly strong, the somewhat subjective analysis of the photographic records is satisfactory. However, where more detailed results are required or where the data is more difficult to interpret, as in the case of stream bed discharges, then digital image processing techniques offer a method of determining relative surface temperatures.

The analogue electrical signal recorded on the magnetic tape can be converted into a digital format suitable for computer analysis. Each scan line of data is divided into 696 discrete pixels each of which is assigned one of 255 grey levels according to the intensity of the thermal infra-red radiation associated with that pixel. By comparing the grey levels with the black body calibration data, the apparent surface temperature corresponding to each pixel can be determined.

Sections of the flight lines were selected from the quick look photographic records for digital processing. The Harwell Image Processing System was used for the 1981 data processing while an International Imaging Systems ($I^2S$) was used for the 1982 data. These image processing systems offer a wide range of algorithms designed to highlight and quantify regions of the image having particular properties.

Selected areas of an image are viewed on a video display unit in a similar form to the photographic records. Regions of interest can be magnified but as this also magnifies the pixel size it tends to produce an image on the screen resembling a mozaic. Having selected the area or region of interest, the grey level spectral range across the image can be plotted as a histogram on the screen. Specific colours can be assigned to narrow sections of the spectral range and the image presented on the screen in such a colour coded format. Although helpful, this technique can lead to a complex image with a high level of superfluous information. A more useful technique is to identify a particular spring or group of springs on the image and determine the spectral (and therefore temperature) range associated with the immediate vicinity around these springs. The image processor can then be used to identify all other zones on the image with similar characteristics, to the exclusion of all superfluous information. This technique is referred to as density slicing. Colour coding the resulting image enables temperature gradients downstream of stream bed spring discharges to be quantified and also provides a technique for identifying zones in the bed of the larger streams and rivers where groundwater inflow is taking place.

## 6. THE SURVEY RESULTS

The most striking aspect of the results from the survey is the wide distribution of groundwater discharges in the Altnabreac area. An analysis of the photographic records, coupled with field visits, identified three general categories of spring. These are:-

a) distinct point discharges emanating into the headwaters of streams or along stream and river bank sides. This category also includes springs discharging along the steeper slopes of hillsides.

b) more diffuse discharges into the beds of streams or rivers.

c) springs which manifest themselves as thermal anomalies on the surface of dubh lochs or some of the larger lochs.

Over 300 springs and groundwater discharges were apparent from an analysis of the photographic records and following digital processing. Many of these were subsequently visited for verification and to allow samples to be collected for chemical analysis.

In many instances the stream and river bed discharges were only evident following digital processing, and only a relatively small proportion of the total survey data was processed in this way. Furthermore, sections of the proposed survey area were not covered at all and some of the data that was collected was of poor quality owing to adverse environmental factors. Therefore, even though a large number of springs were identified during the survey, the fact that no spring was located at a given place does not necessarily mean that no groundwater discharge occurs at that place. This is especially so for the rivers and streams.

The greatest number of springs identified, both numerically and in terms of the apparent cumulative groundwater flow rate, were those issuing either from beneath the surfaces of streams and rivers or from the bank sides close by. Although no estimate of flow rate was attempted from the linescan results, the follow up field work visited over seventy of the springs for sampling purposes and, where appropriate, a rough estimate of flow rate was also made. Flow gauging in three of the rivers over a period of time indicated that the base flow for these catchments is equivalent to an infiltration rate of approximately 100 mm per year. The estimated flow from the distinct point discharge type springs accounted for about 30% of this figure while the remaining 70% was attributed to inflow into the beds of the streams and rivers.

The fact that a high proportion of the flow to the streams and rivers is groundwater derived, and that the headwaters are often formed by springs, leads to the question; which came first, the surface water drainage system or the groundwater discharge pattern? More specifically; did the surface water run-off gradually erode the soft peat and glacial deposits to a depth such that the water table was intersected, thereby further augmenting the flow of the streams and rivers; or is the pattern of spring discharges an inherent feature of the groundwater flow system which provided a basic network to be further developed by surface run off? In the former case it would be expected that the springs represent relatively recent and chemically imature near surface groundwaters circulating through the superficial deposits and weathered granite, and bearing no apparent correlation with the geology or structure of the area. In the latter case it would be expected that the springs represent older and more mature groundwaters upwelling from deep within the rock and bearing distinct correlation with the geology and structure.

When visited in the field, it was found that the headwater type springs are characterised by medium to low conductivity values and are chemically quite different from the surface waters into which they flow (Kay and Bath, 1982). The low conductivities of some of the hillside springs indicate that they probably represent recently infiltrated groundwater which re-emerges due to either a sharp change of slope of the ground surface, bringing it into coincidence with the water table, or as a result of local hydraulic conductivity variations associated with geological structure.

In many areas some of the smaller tributary streams indicate minor groundwater discharges feeding them. However, artificial ditches dug to drain the peat rarely show any groundwater component. This seems to suggest longer residence times for the groundwater discharges than would be expected simply from near surface peat drainage.

Because of the difficulty of being able to determine the precise location of stream bed springs on the ground, these have not been specifically sampled, but they are unlikely to differ greatly from the springs issuing from the sides of the streams. In the lower reaches of the streams and rivers these bank side springs have characteristically higher conductivities and probably represent the most mature groundwaters detected by the survey.

The most intriguing springs are those found in the dubh lochs and the lochs. Many of the dubh lochs are in relatively flat plateau-like areas but often with higher ground to one or more sides. Although no boreholes were drilled in these areas to verify water levels, it is thought that the dubh lochs represent regions where the groundwater surface is coincident with the ground level. Together with the lack of natural drainage due to the low relief, this results in the dubh loch areas being permanently saturated throughout the year. This is in contrast with the change from saturated to unsaturated conditions, observed for other peat covered areas, during prolonged periods of low rainfall. Although spring flows into the dubh lochs are invariably low, the temperature contrasts can be quite high and the water levels in adjacent dubh lochs are often different. Despite the supposition that dubh lochs represent the groundwater surface, the chemistry of the spring waters is not only very similar to that of the other dubh loch waters, but also to that of local rain water. Therefore the majority of the recharge to dubh lochs seems to be from rainwater, while the springs seem to be locally recirculated rather than deeper, more mature groundwaters.

Large discharge zones into the larger lochs are difficult to satisfactorily explain. Even so, these are often closely associated with dubh loch fields into which groundwater springs are issuing. Indeed, if the dubh loch fields do represent the groundwater surface then it would not be surprising to find discharges into nearby lochs which lie on a slightly lower topographic level. What is perhaps surprising is the size of these discharges in terms of their apparent flow rate. It is of course, very difficult to gauge the flow rate simply in terms of the physical size or temperature contrast of the thermal anomaly, especially when it is discharging into the bed of a loch or stream. But the size of the anomaly at the outlfow point from Loch na Cloiche, and the fact that its effect is measurable for at least 150 m downstream, indicates that the flow is not insignificant.

It is also worth observing that many of the streams and tributories which rise from lower ground around the edges of the dubh loch fields are spring fed. This again lends credence to the supposition that the dubh lochs represent the coincidence of the groundwater surface and ground level and that these spring derived tributaries not only form the headwaters to the rivers but also provide the natural drainage from the dubh loch fields, whose groundwater levels are in turn maintained by local topography.

In addition to the on-site chemical characterisation, more detailed laboratory analyses were carried out on samples collected during the field visits. Kay and Bath (1982) carried out such analyses, including inert gases and tritium, and concluded that most groundwaters sampled within 40 m of the surface are dominated by recharge within the last 30 years. Preliminary flow modelling further endorsed this conclusion by suggesting that the groundwater flow is almost horizontal, is related to topography, and would be unlikely, except in anomalous circumstances, to be very great at depth.

In general, attempts to match spring locations with geological features have met with little success, although a few tentative lineations are possible. The spring locations seem to indicate potential lineations, especially along the Rumsdale and Sleach valleys, but these exactly match the NW-SE line of the survey flight paths and so little credence can be placed upon them, especially since they do not match the major fracture orientations mapped by McEwen and Lintern (1980). There is, furthermore, no obvious correlation between spring locations and zones of apparent high transmissivity identified by Glendining (1980).

The overall conclusion, therefore is; that the pattern of groundwater spring discharges does not noticeably correlate with geological and structural features; that the groundwaters are, in general, dominated by waters of recent meteoric origin; and that the springs, for the most part, represent near surface groundwaters circulating within the superficial deposits and weathered granite. Mature groundwaters upwelling from deep within the granite seem likely only on a localised basis when associated with major fault and fracture zones and were not positively detected during this survey.

## 7. CONCLUSIONS

It has been demonstrated that the thermal infra-red linescan technique is fully capable of locating a variety of groundwater spring discharges which, in most cases, would otherwise have been very difficult to identify. It was, however, apparent that the optimum survey conditions, in terms of groundwater flow rate and temperature contrast, occur at a time of year when unsettled weather conditions are likely to lead to only a few (unpredictable) days being optimum for flying. Even then, the adverse effects of solar heating restrict the flying time to a few hours during the early morning of each day. If precise navigational aids were to become available, which would allow low level flying during the hours of darkness, then the survey flying time could be considerably increased thereby increasing the chances of being able to complete the survey with good quality data during limited weather windows.

With good quality data an adequate interpretation of spring locations can be obtained from the photographic records. But with poor quality data, or where more detail of stream bed spring locations or quantitative temperature distributions are required, the digitally processed colour coded images provide a much clearer interpretation. Digital processing also enables some of the subjective aspects of the interpretation to be reduced by being able to highlight only those areas of interest. Digital processing, however, requires the provision of sophisticated image processing equipment with the appropriate level of user expertise, and it can be time consuming.

The number and distribution of springs located by the thermal infra-red linescan survey has proved to be far greater than had been anticipated. The springs were categorised into three general types, of which the most anomalous were those issuing into the dubh lochs and larger lochs, but the most numerous were those providing the base flow to the streams and rivers. Indeed, it seems that a high proportion of the flow to the streams and rivers is provided by groundwater inflow.

The results from this survey, together with the geochemical and hydrogeological work of others, indicates that the groundwater table is strongly influenced by local topography and that the majority of the spring discharges represent near surface recent groundwaters circulating within the superficial deposits and weathered granite.

## 8. ACKNOWLEDGEMENTS

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