Lineaments in groundwater exploration: a review of applications and limitations

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Introduction

The mapping of linear features on various types of maps or remotely sensed data is one of the keys to understanding groundwater occurrence, especially in areas with igneous and metamorphic rocks of poor primary porosity, commonly referred to as hard rock terrain. Lineaments mapped with remote-sensing data have therefore been the focus for targeting well sites for many decades, albeit with varying success. Sometimes lineament mapping, regardless of geologic environment, is believed to be the panacea for successful groundwater exploration. Numerous papers and reports have been produced showing lineaments as the backbone of the investigations, with more or less impressive results. The mapping and interpretation of lineaments needs to be done with care and with a proper understanding of its applications and limitations. This is not always the case. Here, an overview of lineaments in groundwater exploration is presented, with some examples of both successful approaches and potential pitfalls.

Lineament definition and history

Numerous definitions of the term 'lineament' are given in literature and various attributes are sometimes linked to the term—such as 'geologic lineament', 'tectonic lineament', 'photo lineament' or 'geophysical lineament'—either describing the assumed origin of the linear feature or sometimes the data source from which it has been derived. Some workers also use the term 'fracture trace' or 'photo linear' as an alternative term. The work by Lattman and Parizek (1964) is commonly regarded as pioneering work in groundwater exploration; they mapped linear features (fracture traces) on stereo-pairs of aerial photographs in carbonate terrain in the eastern United States, and subsequently showed the correlation between well productivity and distance to the identified features.

Lineament mapping was used long before this work in other geological applications and the first usage of the term lineament in geology is probably from a paper by Hobbs (1904), who defined lineaments as significant lines of landscape caused by joints and faults, revealing the architecture of the rock basement. This was later used by O'Leary et al. (1976) and Waters et al. (1990) as a basis for developed definitions.

Exploration approach

Over the four decades since Lattman and Parizek's paper many projects have employed lineament mapping as the core of the groundwater exploration work, especially in complex geologic environments (e.g. Mabee et al. 1994; Minor et al. 1995; Solomon and Quiel 2006). The success rate of projects varies considerably and is clearly not only related to the variation in geologic and hydrogeologic conditions, but also to the overall exploration methodology, the quality and coverage of available data and the experience and profession of the personnel involved. Some projects have a strong focus on the image-processing component, some projects focus on structural geology and tectonic history, while other projects follow a strongly geophysical approach. Ideally, a project draws on experience from all these categories to achieve optimum results.

Groundwater exploration programmes involving the use of geographical information systems (GIS) commonly employ a 'top-down' hierarchical approach in which data from various sources and of various scales are integrated to identify suitable targets. Typically, groundwater exploration in a rural water supply project commences with collecting and analysing various types of data available for the project area such as maps, remote-sensing data, geophysical surveys, borehole data and climatic records. Commonly the data exhibit poor spatial completeness, heterogeneous coverage of key parameters, difficult control of uncertainty and incompatible coordinate systems, causing decision-making to be challenging.

Common to most successful projects is the understanding that water-well drilling in many hard rock areas is associated with a high risk of failure and therefore calls for the best tools to be used. The success of a project relies upon the decision-maker, whether a geologist, hydro-

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geologist, engineer, economist or other professional, to make the right choice when weighing the cost-effectiveness of various investigation techniques against the risk of drilling an unsuccessful borehole.

The drilling of an unsuccessful well is almost as costly as drilling a successful well, the only difference being the cost of equipping the well. In a rural water-supply project in Ghana (Minor et al. 1995), remote sensing and GIS analysis formed the core of a new exploration strategy to improve success rates in difficult geological settings. The previous success rates, using mainly field mapping and sometimes geophysics, varied between 25 and 70%, with an average of 57%. An economic analysis was carried out on a 500-well programme to evaluate the cost-benefit of employing a new systematic remote sensing and GIS approach, including rigorous lineament mapping and interpretation, to increase success rates. Even with a moderate increase in success rate from the previous 57 to 70%, the value of employing a remote-sensing approach was found to be around US $750,000 for the 500-well programme. More important was the fact that the programme would take almost 1 year less to complete, thus providing faster access to safe water supplies.

The cost-effectiveness of applying good base work before drilling commences is often overlooked. Many groundwater exploration programmes still rely heavily on geophysical site surveys followed by extensive drilling campaigns. A thorough analysis of existing spatial data, including remote sensing, is sometimes restricted to research oriented projects, with less benefit to communities with inadequate water supplies. Clearly, lineaments alone are not the answer to successful groundwater development. Many other factors are equally important in order to separate 'the good' from 'the bad' drilling sites, including, for example, a proper understanding of tectonic processes, local lithology, recharge processes and groundwater quality. In addition, mapped linear features can represent a variety of geological phenomena. Many groundwater development projects have also shown that political or socioeconomic conditions override geological factors and dictate the choice of drilling sites more than the responsible hydrogeologist appreciates.

The mapping, the interpretation and the real world

Lineament mapping is the process of drawing lines on maps and images; interpretation involves an understanding of the mapped features and adding value. In the real world, the best sites may be far away from the lineaments, or lineaments should be avoided or there is really nothing 'linear' available in the area where it is needed.

Mapping of linear features can be carried out on a wide array of sources such as geophysical data (e.g. aeromagnetic images), topographic maps, digital elevation models (DEMs), radar data or, most commonly, on various types of optical image data such as satellite images or aerial photographs. Potential optical satellite imagery for lineament mapping includes very high spatial resolution data such as QuickBird and IKONOS, with down to sub-meter resolution. The typical cost (2006) of QuickBird data of around US $20 per km^2, however, prohibits its use in most water-supply projects. The most commonly used satellite imagery is from the medium resolution Landsat, SPOT, IRS and ASTER missions. These data have a cost per area ratio starting from a few US cents per km^2 and a spatial resolution between 2.5 and 30 m. In addition, they have a much larger spectral resolution, providing opportunities to do so much more than lineament mapping. This includes mapping the distribution of lithological units, geomorphology, drainage systems, surface water sources, soil moisture, vegetation patterns, etc., which all assist in the hydrogeological characterisation of a project area. ASTER data are probably the best choice for a groundwater project, due to their large spectral resolution, reasonably high spatial resolution, possibility to derive DEMs and low cost of acquiring the imagery. Drury and Andrews Deller (2002) provide a good overview of satellite imagery in groundwater development such as ASTER and Landsat.

Aerial photography is usually used as a complement to satellite imagery, especially for detailed fracture mapping and for pinpointing sites for detailed field investigations. Unfortunately, many rural areas in the developing world are only covered by old air photos available as paper prints in dusty archives, which makes their integration with digital data a greater challenge. Despite this, air photos should always be considered and where possible integrated into the groundwater exploration approach. Moreover, old air photos can provide clues to important structural features now obscured by the current land use, and they can usually be interpreted in stereo, allowing a better understanding of the tectonic setting of the area.

The mapping of lineaments commonly takes place in a digital environment using either image processing systems or GIS. The mapping is usually either completed close to where well sites are needed or with more or less complete coverage of entire regions. Some projects, mainly research oriented, have also used automatic lineament extraction in which the operator tries to avoid the subjectivity inherent in manual mapping. The resulting lineament maps from different approaches are therefore very different.

Lineament mapping has often been criticised for the poor reproducibility between different operators and the apparent random distribution of lines without support of a proper geologic understanding of the area. Confidence in lineament maps can be increased through the integration of results from several operators mapping lineaments of the same area. Some ideas on this concept were provided by Sander et al. (1997). In that study, the operators individually mapped and simultaneously classified the lineaments into three categories of hydrogeological significance based on prominence, vegetation evidence and alignment with drainage and topography. The results showed that the perception of linear features were significantly different between the three operators, with a large variation in length and location of individual line segments. The study revealed, however, that upon closer examination of the results, all operators had to a large degree mapped the same inferred geologic feature, albeit

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with a different approach and with slightly deviating positions. The study also showed that lineaments classified into the highest hydrogeological significance category had very good agreement between operators, thus justifying the use of classifiers in lineament mapping.

Kellgren (2002) and Kellgren and Sander (1997) provide some ideas on how lineaments can be systematically mapped and classified to ensure that their hydrogeological significance is considered in the process. They suggest a classification into four categories based on a semi-arid study area in South Africa. Lineaments are manually classified into four categories during the on-screen digitising, based on their association with topography, drainage and vegetation. Three classes of potential fracture zones and a fourth class representing dykes are introduced. The latter usually has a different expression on remote-sensing imagery as well as dissimilar hydraulic properties and calls for a different siting strategy. The approach was tested extensively with ground geophysics and exploratory drilling, showing a significantly increased success rate and economic advantage in well drilling compared to the traditional exploration methodologies previously employed in the same area.

It is important to remember that lineaments of geologic origin are essentially a two-dimensional representation of a three-dimensional phenomenon and their mapping on remote-sensing imagery provides little direct information on the type of feature and its depth, dip and potential infilling. Lineaments, therefore, need to be integrated with other data to enable a correct geologic interpretation and understanding of their hydrologic function. The use of GIS, in which the lineaments can be analysed with other supporting 'evidence' data and continuously updated when new data become available, is consequently a key to project success.

Applications and limitations

Lineament mapping and interpretation is sometimes executed in such a way that the original objective of the exercise is neglected, i.e. providing water supplies in the areas where they are most needed. The practical use of the results is sometimes compromised in favour of advanced image processing algorithms and numerical wizardry of mainly academic interest. Significant research funds have been spent on attempts to automate the lineament mapping process, for example with the use of neural network analysis or contextual mapping. The application of these methods to a typical rural groundwater exploration programme in a problematic geologic environment is, however, questionable. The necessary weeding of the results and the influence of local factors exemplified below will be preventive.

Over the years, numerous papers and reports have been published, displaying an array of techniques to analyse lineaments and their geologic origin and transmissive properties. Some have used fairly straightforward field investigations such as geophysics and/or drilling, to explore the groundwater potential of mapped features (e.g. Chandra et al. 2006). Others have employed tectonic models, inferred stress regimes, or detailed structural mapping to identify potentially favourable lineament azimuths (e.g. VIAK 1984). Yet other workers have used borehole records to prove certain types of lineaments or specific azimuths as more promising for groundwater development (e.g. Tam et al. 2004).

The techniques discussed above and many others, hopefully, all have their benefit depending upon the geologic setting and other conditions. There are, however, occasions where the chosen approach is detrimental to the success of the project. The following points summarise (not in order of importance) some typical circumstances and problems when lineaments are used as the basis of groundwater development in rural water-supply programmes in hard rock areas.

- The best targets for sustainable well sites are located where fractured zones can interact with storage in overlying unconsolidated material, which also means that the fracture zones are concealed and cannot easily be identified on the remote-sensing data. Suitable sites then have to be extrapolated from mapped features in surrounding areas, consequently with less accuracy.
- Statistically significant borehole populations with reliable information are very seldom available to give conclusive results regarding certain lineament azimuths as more promising than others. Borehole records often have poor positional accuracy or little hydraulic data. In addition, statistical analyses using borehole populations and proximity to lineaments, seldom acknowledge that a borehole located in the extension of a mapped feature is likely to have a higher capacity than a borehole perpendicular to a mapped feature, despite being further away.
- There is sometimes an exaggerated faith in hydrotectonic models and impact of original or present stress regimes when analysing lineaments. Obviously, large compressional stress perpendicular to the mapped feature will to some extent negatively affect its transmissive properties, while compressional stress parallel to the inferred fracture zone will tend to open the feature (Banks and Robins 2002). However, local factors such as fracture infilling and fracture connectivity, may have a larger impact on the productivity of the feature. In addition, for many project areas, the current stress regime is not known.
- The hunt for major lineaments and lineament intersections as targets can be discouraging as the presence of clay gouge in many geologic environments effectively reduces the permeability, despite the feature obviously being intensively fractured. The best targets may instead be on the margins of the larger lineaments or in close proximity to less conspicuous features.
- Lineament density maps are popular, but of limited use in most cases. Groundwater potential maps are often constructed with lineament density maps as the core, even in terrain where the location of successful wells is heavily dependent on a rather precise projection of well sites. A few tenths of meters may in some areas mean the difference between high capacity and dry, and a regional groundwater potential map is then not much help. In addition, high lineament and drainage density may

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imply poor recharge conditions rather than areas suitable for groundwater exploration.
- A limit in the search for exploration targets to within a short distance of community centres greatly reduces the potential of finding promising sites. Not only is there an exponential increase in the search area with increase in search radius, the number of possible sites also increases because the effects of land use usually decrease away from the community. In addition, two or more communities may be able to share a reticulated water-supply system if the well sites are favourably located.
- Many communities are located on the interfluves between drainages where the number of available targets is considerably less than targets adjacent to drainage channels, thus further encouraging a larger search radius from the community.

A good understanding of local geology, including lithology, tectonics, recharge mechanisms, storage capacity of unconsolidated material, groundwater chemistry, etc. is undoubtedly important when identifying targets for detailed investigations. The synthesizing of information in a GIS is an excellent methodology, albeit time-consuming and fraught with many deceiving problems such as spatial incompleteness, spatial uncertainty and coordinate inaccuracies. With that in mind, GIS still greatly facilitates the analysis of factors contributing to drilling success and additionally gives personnel with different concepts a platform to test various hypotheses.

Discussion and conclusions

What advancements have emerged over 40 years of lineament mapping and interpretation in groundwater exploration? Has the development of new image sensors with very high spatial and spectral resolution data made groundwater exploration more effective? Has a successful interpretation of the meaning of these linear features increased the drilling success in a typical water-supply project? The answers are both yes and no. Many projects still suffer from unacceptably low success rates, while others have effectively incorporated image processing, lineament interpretation, and GIS integration in the development of groundwater resources. Unfortunately, many groundwater exploration programmes instead suffer from low success rates due to political and economical barriers which are beyond the control of the lineament analysts.

So what is the status of lineament interpretation today? The availability of image data for the interpretation of groundwater indicators is certainly better and cheaper. Hardware and software have dropped to acceptable prices and can be used even in small local projects. In addition, access to global positioning systems and various Internet resources has increased tremendously.

The easy access to a decision platform for well siting, based on remote-sensing imagery, GIS and various peripheral tools is a great improvement, but also presents a risk, as it is easier to use them unwisely. It is, therefore, essential that lineament application experiences from successful ‘real’ water-supply projects are shared in the hydrogeological community and that training and capacity building forms an integral part of the projects.

So what will happen in the future? Will new satellite sensors and new interpretation and analysis techniques provide opportunities that cannot be imagined today? Maybe so, but the reality is that knowledge and resources are already available and there is no excuse as to why such a large proportion of the world’s population is still living in areas without a proper water supply. Properly sited wells in drought-stricken areas could change the lives of many, and the remote-sensing analysts and lineament interpreters around the world are without doubt important in this process.

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