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BASIN DEPTH ESTIMATION USING SCALING PROPERTIES OF POTENTIAL FIELDS

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Abstract

The power spectrum of potential field data in a horizontal observation plane decays the faster the greater the depth to source. This property is often utilized for estimating the depth of sedimentary basins. Some popular methods of depth estimation by spectral analysis assume that the depth factor dominates the shape of the log radially averaged power spectrum. However, the power spectrum can also be dominated by the statistical properties of the source distributions, which can be described by the concept of scaling geology. We derive a model power spectrum consisting of a depth term, a term accounting for scaling properties of the source distribution and a noise term. Interpreting power spectra with this model we obtain depth values which differ significantly from the depth values derived by earlier methods of spectral analysis. In particular, there is a certain trade-off between the statistical properties of the source distribution and the depth to source. Hence, a reliable estimate of the basin depth may require a priori information on the individual statistical properties of the source distribution in a particular basement.

Introduction

Potential fields look smoother the greater the distance between the observation plane and the sources of the field. The reason is that short wavelength anomalies can only be resolved at a close distance. Hence, a potential field originating from the crystalline basement of a deep sedimentary basin is dominated by long wavelength anomalies. This observation can be quantified by regarding the power spectrum of the data.

A method which estimates the depth to source from the radially averaged power spectrum of aeromagnetic data was first proposed by Spector and Grant (1970). This method was developed further by Naidu (1972) and by Hahn et al (1976). Spectral analysis has also been applied to gravity data. These methods of spectral analysis have in common that they assume the depth to source to dominate the shape of the log radially averaged power spectrum. This is equivalent to assuming a constant power spectrum at source level.

However, to assume a constant power spectrum at source level may not always be appropriate. Pilkington and Todoeschuck (1993) showed on well-logs that the susceptibility distribution in the Earth's crust is scaling. Scaling distributions have a power spectrum which is proportional to some power γ of the

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wavenumber f, i.e., $P(f) \propto f^{-\gamma}$ (Mandelbrot, 1983). Scaling susceptibility and density distributions cause magnetic and gravity fields which are again scaling (Pilkington and Todoeschuck, 1993: Maus and Dimri, 1994). In this paper we want to demonstrate that taking into account the scaling properties of potential fields leads to more reliable estimates for the depth of sedimentary basins.

Theory

Up and downward continuation. Say, we have measured the anomaly of the total intensity of the magnetic field in a horizontal observation plane at $z = h = constant$. We can estimate the two-dimensional (2D) power spectrum $P_h(k_x, k_y)$ from the data (Spector and Grant, 1970). Let us assume that the statistical distribution of the source magnetization in the ground is horizontally isotropic. Further, let us assume that the principal direction of magnetization is parallel or antiparallel to the normal field. Then the 2D power spectrum can be reduced to the pole and the resulting 2D power spectrum is expected to be isotropic. For an isotropic power spectrum we can consider the radial average $\overline{P_h}(r)$ defined by

$$\overline{P_h}(r) = \int_0^{2\pi} \overline{P_h}(r \sin\theta, r \cos\theta)\, d\theta \qquad \text{.................(1)}$$

Let us assume that there exists a definite upper edge of the sources as illustrated in Fig.1. This magnetic basement may be the crystalline basement of a sedimentary basin with virtually nonmagnetic basin fill or simply the surface

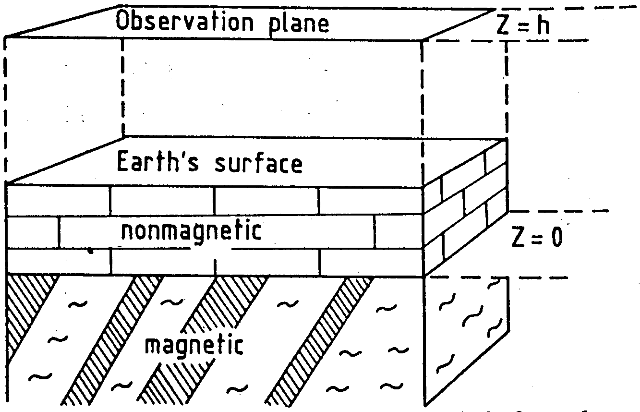

Fig. 1: We use a simple model for the estimation of basin depths. Nonmagnetic sediments covering a crystalline magnetic basement. The observation plane is located in a certain height above the Earth's surface. The coordinate system is placed in such a way that $z = 0$ at the basement of the basin.

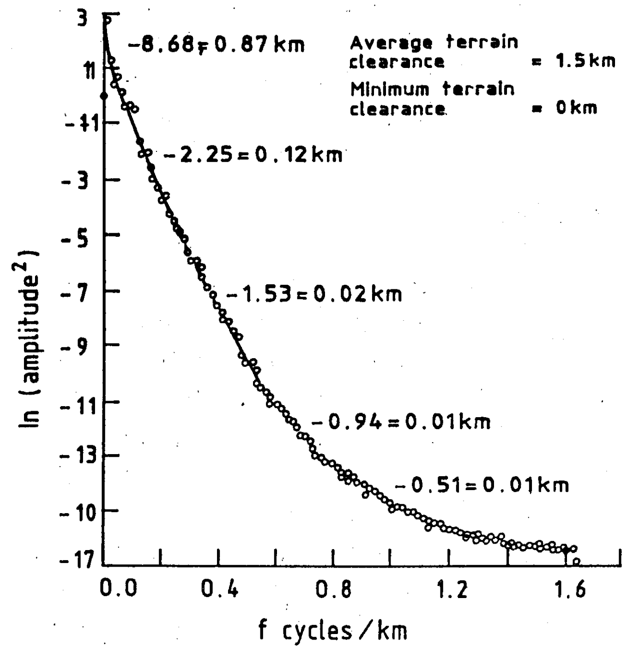

Fig. 2: This figure demonstrates the use of the Spector and Grant method. The slope of the power spectrum is assumed to be proportional to the depth of magnetic interfaces. Consequently, the depth values can be derived directly from the slope of the power spectrum (after Connard et al., 1983).

of the Earth. If we place the coordinate system in such a way that $z = 0$ at the top of the sources then the power spectrum $\overline{P_h}(r)$ in the observation plane can be related to the power spectrum $\overline{P_o}(r)$ at the top of the sources by

$$\overline{P_h}(r) = e^{-2hr}\,\overline{P_o}(r) \qquad (2)$$

Equation (2) is the well known relationship for upward and downward continuation of potential fields in a medium free of sources.

In equation (2) usually only $\overline{P_h}(r)$ is known, which can be estimated from the potential field data measured in the observation plane. If we also had an idea about $\overline{P_o}(r)$ we could calculate the factor e^{-2hr} from (2) and thus estimate the depth to the top of the sources. Hence, this relationship is of great practical importance.

Spector and Grant's method. The easiest way to make use of equation (2) is to assume $\overline{P_o}(r) \equiv constant$. This was first proposed by Spector and Grant (1970). Taking the logarithm of equation (2) we then get

$$\ln(P_h(r,\theta)) = -2hr + c \qquad (3)$$

and thus the slope of the log power spectrum is directly proportional to the depth to source. The Spector and Grant method is demonstrated in Fig. 2. To derive to source directly from the slope of the log power spectrum of magnetic and gravity data is very convenient and enjoys continuing popularity as can be seen from a number of recent publications (e.g. Ofoegbu and Hein, 1991; Cowan and Cowan, 1993; Hildenbrand et al., 1993; Pawlowski, 1994). Unfortunately, the depth values derived by this method are not always very reliable. Fig.3 for example, shows the basement topography of the Northern German Basin derived by the Spector and Grant method as solid lines (after Hahn et al., 1976), overlaid with the depth values derived by other geophysical methods as dashed lines (after Ziegler, 1982). A significant discrepancy is observed between the two maps. Possibly, the assumption of $\overline{P_o}(r) \equiv constant$ is unrealistic in this case.

Studying P_o. To obtain a reliable estimate of the depth to source using equation (2) requires a realistic assumption on the shape of the power spectrum directly above the sources, $\overline{P_o}(r)$. We will now regard an example from Hawaii where the ground consists of highly magnetic basaltic lava. Here, the top of the sources is obviously identical with the surface of the Earth. The radially averaged power spectrum $\overline{P_o}(r)$ at surface level is displayed in fig. 4 in single logarithmic scale. The log power spectrum is not constant but decays exponentially. Plotting the curve in double log scale (Fig.5) yields a straight line, hence

$$\ln(\overline{P_o}(r)) = -\gamma \ln r + k$$
$$(\overline{P_o}(r)) = k\, e^{-\gamma}, \qquad (4)$$

where k and γ are constants.

The power spectrum defined by equation (4) is the power spectrum of a *scaling noise* (Mandelbrot, 1983). The constant γ is called the *scaling exponent* of

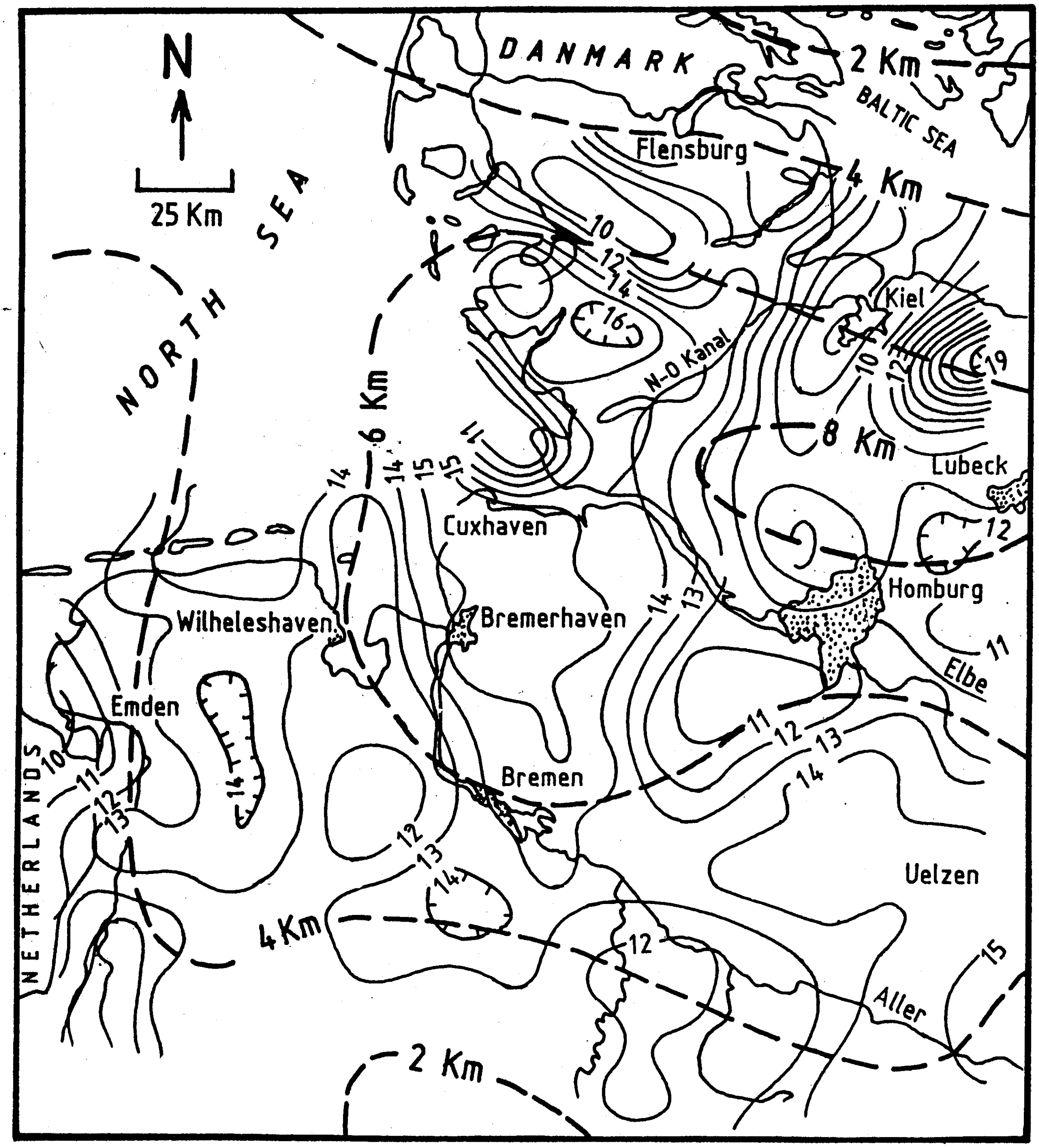

Fig.3: Isoline map of the basement topography derived by Hahn et al, (1976) by the Spector and Grant method for the NW-German Basin. The dashed lines indicates the correct basement depths (Ziegler, 1982) for this area. A significant discrepancy is observed between the two maps.

the scaling noise. Pilkington and Todoeschuck (1993) observed that the susceptibility distribution in the Earth's crust is scaling. Further they discovered that a halfspace of scaling sources leads to an anomaly of the magnetic field at source level which is again scaling in the sense of equation (4). A similar relationship also holds for gravity data (Maus and Dimri, 1994). Combining equations (2) and (4) we receive a power spectrum

$$\overline{P}_{model}(r) = ke^{-2hr} r^{-g} , \qquad \text{................(5)}$$

which is useful for understanding the shape of the power spectra of potential field data.

Applications

A power spectrum of aeromagnetic data of a sedimentary basin with essentially nonmagnetic basin fill is displayed in Fig.6. The depth of the basin is known to be around 1400m. Together with the flight altitude of 300m the correct depth to source is 1700m.

The solid lines indicate model power spectra defined by equation (5) for different values of the scaling exponent γ. The depth to source h and the constant k have been chosen in such a way that an optimum fit of the model to the observed power spectrum at low wavenumbers is achieved in a least squares sense.

We notice that the model power spectra do not explain the observed powers at high wavenumbers satisfactorily. The observed powers at high wavenumbers are higher than the model powers. This can be explained by the presence of high frequency noise. Some of this noise may also be attributed to a non-negligible magnetization of the sediments. The presence of high frequency noise is a well known problem which is usually overcome by cutting the power spectrum and discarding the high wavenumber portion as noise (Spector and Grant, 1970; Hahn et al., 1976).

A refined model. Another possibility is to extend the model power spectrum by including a term for the noise. Mandelbrot (1983) observed that noises are usually scaling. Hence a term $k_n r^{-\gamma n}$ may be appropriate to model the noise. Assuming that the noise is statistically independent of the signal we can add the noise term to the model power spectrum, resulting in a refined model power spectrum

$$\overline{P}_{redefined}(r) = k\, e^{-2hr} r^{-\gamma} + \kappa_n \rho^{-\gamma n}, \qquad \text{..................(6)}$$

where k_n is the intensity and γ_n is the scaling exponent of the noise.

Before applying this refined model, a second observation is made from Fig.6. We can see that there is a certain trade-off between higher values of the depth h to the top of the sources and lower values of γ. Hence, a reliable estimation of the depth to source appears to be impossible if both h and γ are unknown. This problem cannot be overcome by using a refined power spectrum such as (6). It appears, rather, that this is a fundamental problem of the method: To obtain a reliable depth estimate, the statistical properties of the source distribution, i.e. the scaling exponent

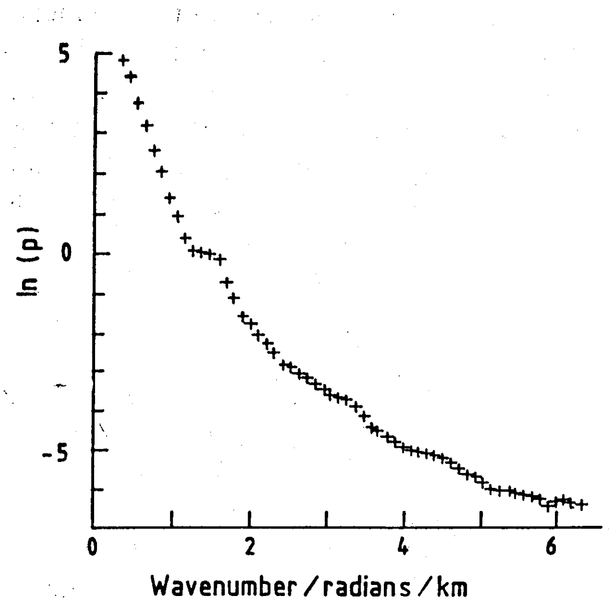

Fig. 4 : Radially averaged power spectrum of aeromagnetic data of Hawaii continued downward to ground level in single logarithmic scale (data after Hildenbrand et al., 1993)

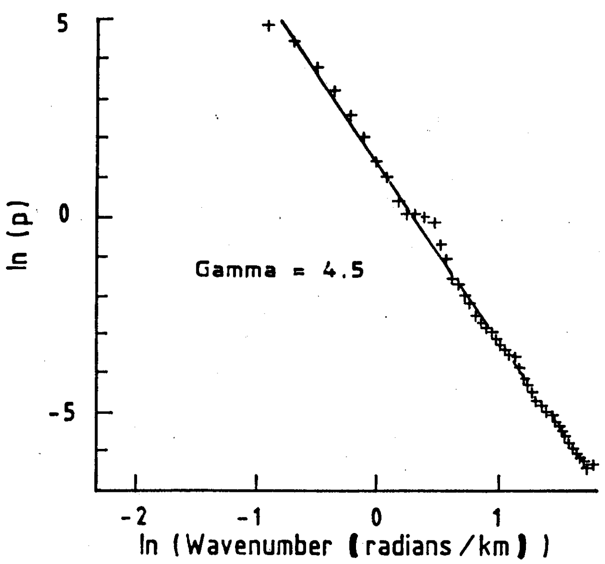

Fig. 5 : Power Spectrum of Fig.4 in double logarithmic scale. The linear shape of this power spectrum indicates scaling properties of the field immediately above the sources.

of the source magnetization, has to be known.

Including a priori information on. Let us recall that γ is the scaling exponent of the field immediately above the sources. Gregotski et al.(1991) have analyzed aeromagnetic data of the North American continent and found a mean scaling exponent of $\gamma = 3$. Using this value as an estimate for the scaling exponent of the field caused by the basement in the example of Fig.6, we receive an optimum value of h = 1050m minus 300m for the flight altitude as possible depth of the basin.

The estimate of the basin depth can be improved if we find an area with outcropping basement of presumably similar lithology adjacent to the basin. In this case we can estimate γ from that area. This procedure is demonstrated in Fig.7. The upper curve (a) is the power spectrum of an area next to the basin. Here, the optimum fit with h = *flight altitude* is obtained for $\gamma = 2.2$. Using this information in our refined model, we obtain a depth of t = 1640m, a signal to noise ratio of k / k_n = 177 and $\gamma_n = 3.3$ as a best fit of the refined model power spectrum to power spectrum (b). This depth value is quite close to the correct depth value of approximately 1700m. Hence, it seems possible to find the depth of a sedimentary basin, using a priori information on the scaling exponent of the field caused by the basement.

Results and Discussion

Downward continuation of potential fields was discussed as a means of

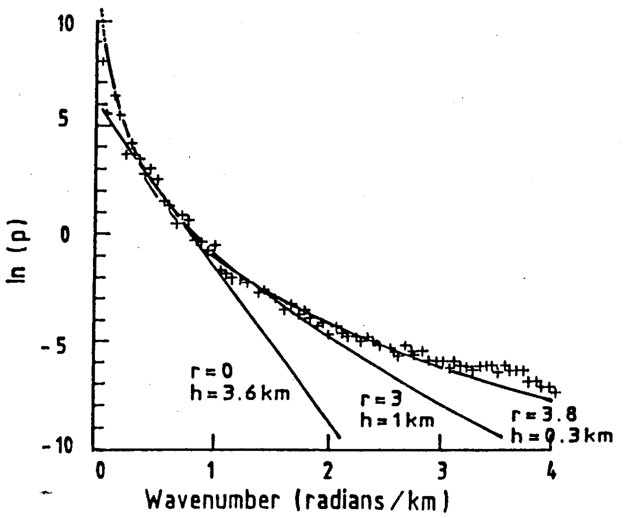

Fig. 6 : Power spectrum of aeromagnetic data over a sedimentary basin (data from Pilkington et al., 1994). The correct depth to source is approximately 1700 m. The solid lines indicate the best fit of the model power spectrum in a least squares sense for some selected values of γ . *For* $\gamma = 3.8$ *the best overall fit obtained,* $\gamma = 3.0$ *is the mean value of the scaling exponent for aeromagnetic data derived by Gregotski et al.(1991) and* $\gamma = 0$ *corresponds to the Spector and Grant method. The smaller the values we assume for* γ, *the greater the estimated depth to source h.*

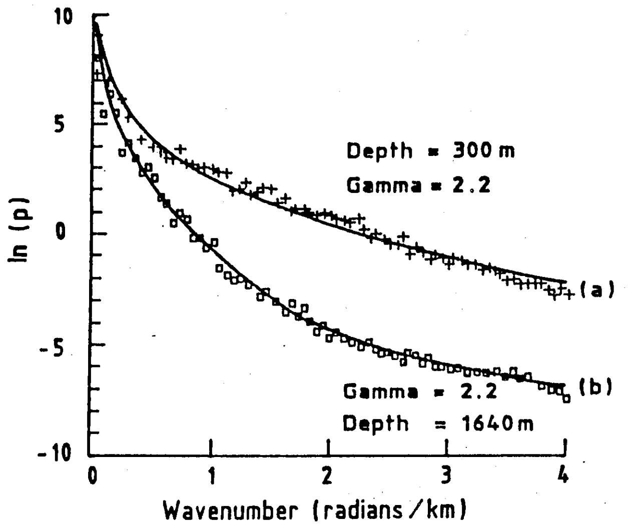

Fig. 7 : Power spectrum of Fig.6 labeled as (b) together with the power spectrum for an area with outcropping basement (a). With the optimum value of the scaling exponent obtained from power spectrum (a), we can estimate the basin depth from power spectrum (b) using the refined model defined by equation (6), assuming identical statistical properties of the magnetic field caused by the basement.

estimating the depth of sedimentary basins. To obtain the correct basin depth the statistical properties of the field immediately above the basement have to be known. These statistical properties can be quantified by the concept of scaling noises. The individual shape of the power spectrum of the field caused by a particular basement is then characterized by a single parameter, namely the scaling exponent of the field caused by this particular basement.

It turns to be difficult (may be even impossible) to obtain the scaling exponent of the basement as well as the basin depth from one and the same power spectrum since there is a certain trade-off between scaling properties of the field and the depth to source. To estimate the depth to the basement, a *priori* information on the scaling exponent of this particular basement may be required. Assuming that a characteristic value of the scaling exponent can be attributed to a certain basement lithology, we have estimated the scaling exponent from an area adjacent to the basin with outcropping basement of presumably similar lithology. This procedure yielded the correct depth of the basin which had been established by other geophysical methods.

The method implicitly assumes that a particular basement lithology causes a potential field with a characteristic value of the scaling exponent. Scaling exponents derived from aeromagnetic data in the area of the German Continental Deep Drilling Project (KTB) support this assumption (Maus and Dimri, 1995). However, further studies will have to confirm that characteristic values of the scaling exponent can be associated with certain basement lithologies and show, whether the scaling exponent remains constant over a large area of a outcropping basement.

Acknowledgments

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