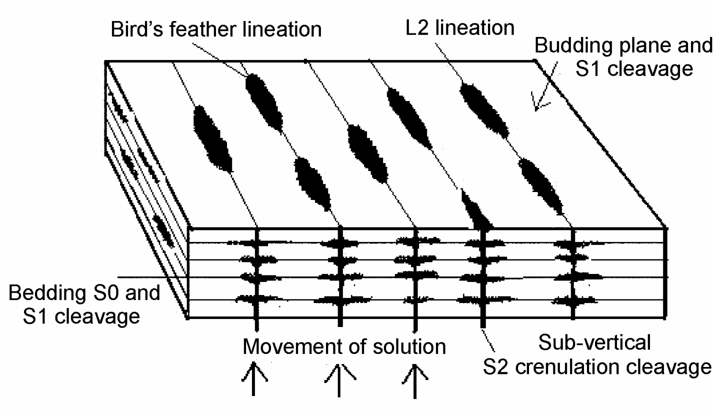

Figure 4. Formation of Bird's feather lineation.

spread along the bedding planes/first-generation slaty cleavage (which are almost parallel to the bedding except in the hinge zones of the first-generation folds) in an elongated pattern forming an unusual type of lineation in the rock[1]. On close examination in each bird's feather-like structure, the solution starts spreading from the centre and spreads outward forming a corona-like structure at the margin (Figure 3). Viscosity contrast between calc-silicate and the pegmatitic material seems to have given rise to the development of lobate and cuspate types of margins[5] (Figures 2 and 3). The patches are sporadically distributed on the surface. They vary from 0.5 to 1 mm in thickness. These structures range from 5 to 12 cm in length and from 1 to 3.5 cm in width. When slightly thicker they give a pseudo impression of highly compressed and elongated pebbles of a conglomerate similar to the one exposed near Barr[3].

The linear structure appears to be unique in its mechanism of formation. Its significance in the structural analysis of complexly deformed rocks is likely to contribute significantly in establishing a relationship between the particular phase of deformation and the time of emplacement of pegmatite in the region. In the present case, the bird's feather lineation has developed due to penetration of pegmatitic solution along the sub-vertical crenulation cleavage planes (Figure 4) associated with the second deformation in the Delhi Supergroup and the structures are oriented parallel to the axis of the second-generation folds. Therefore, the emplacement of pegmatite bodies in the region has taken place during the second deformation in the Delhi Supergroup of rocks.

1. Hobbs, B. E., Means, W. D. and Williams, P. F., *An Outline of Structural Geology*, John Wiley, London, 1976, p. 267, 273.
2. Gupta, S. N. *et al.*, *Mem. Geol. Surv. India*, 1997, **123**, 67–78.
3. Heron, A. M., *Rec. Geol. Surv. India*, 1953, **79**, 339.
4. Gupta, S. N. *et al.*, Lothostratigraphic Map of Aravalli Region, Geological Survey of India, Hyderabad, 1980.
5. Ramsay, J. G. and Huber, M. I., *The Techniques of Modern Structural Geology, Volume 2: Folds and Fractures*, Academic Press, London, 1987, pp. 491–501.

ACKNOWLEDGEMENTS. Help received from Mr S. C. Suthar and Dr G. Rathi, Shree Cement Ltd, Beawar is acknowledged. I thank the anonymous reviewers for their valuable and constructive suggestions.

Received 9 November 2009; revised 15 July 2010

B. S. PALIWAL

Department of Geology,
Jai Narain Vyas University,
Jodhpur 342 005, India
e-mail: paliwalbhawani@yahoo.co.in

Nonlinear electrical conductivity response of shaly-sand reservoir

I would like to draw the attention of the readers to a number of errors in the scientific paper[1]. These errors, taken together, are sufficiently important to make all four of the paper's conclusions invalid.

The paper[1] contains a review of three different approaches to the modelling of electrical conductivity of reservoir rocks composed of two conducting phases. The three approaches are (i) Bussian's model[2], (ii) a model that they call the Mixing model, but which in fact would be better attributed to Korvin[3] or Tenchov[4], and (iii) the model of Glover *et al.*[5]. According to Sri Niwas *et al.*[1], all these equations are nonlinear. A nonlinear system is one in which the variable(s) to be solved for cannot be written as a linear combination of independent components, i.e. it is a system which does not satisfy the superposition principle. Only the Bussian equation fulfils this criterion. Both the Korvin[3] and Glover *et al.*[5] models are linear and can be solved exactly, without recourse to numerical solution.

In their figure 1, Sri Niwas *et al.*[1] purport to show the calculation errors when using the three models. By this they mean the errors induced in using their nonlinear inversion code, which uses the bisection method. The figure correctly shows that the error in the Bussian nonlinear inversion is low (10^{-4} to 10^{-8} S/m). However, it shows the errors for the Glover[5] and Korvin[3] models to be in the range 100–10^{-2} S/m (i.e. much higher). As I have already discussed, the Korvin[3] and Glover[5] models are not nonlinear. They can be solved analytically and exactly using a calculator or a computer. In other words, the error associated with their computation is the same as a computer (i.e. about 10^{-499} S/m) and is independent of the other parameters in the model. It is not clear from the paper how the authors have generated the curves in figure 1 for the Korvin[3] and Glover[5] models. It is possible that the large error values are caused by instabilities in their numerical routines when applied to linear models.

What is clear is that figure 1 is not correct and the conclusions that the authors draw from it are also not correct.

The interpretation of the low fluid conductivity version of the Glover *et al.*[5] equation derived by Sri Niwas *et al.*[1] (their eq. (11)) is wrong in two respects. First, it should not contain an approximatively equal sign but an equality sign because the Glover *et al.*[5] model is equally true for the entire range of fluid conductivities. In other words, eq. (11) of Sri Niwas *et al.*[1] is the same as the general equation for the Glover *et al.*[5] model (eq. (7) in Sri Niwas *et al.*[1]). Second, the Glover *et al.*[5] model is symmetric in the sense that one may swap the two phases without changing the formal structure of the model. The observation in Sri Niwas *et al.*[1] that the low fluid conductivity versions of the three models '... reveals that for a given value of ϕ and for low σ_w, σ_0 is linearly proportional to σ_s in the case of Glover and Mixing equations, whereas it is linearly proportional to σ_w for the Bussian equation.' is correct. This is a strength of the Korvin[3] and Glover *et al.*[5] equations and a weakness in the Bussian[2] equation because it means that the conductivity of the bulk rock is controlled by the matrix when the conductivity of the fluid is too small to contribute. Instead Sri Niwas *et al.*[1] use it to generate the paper's first conclusion; that '... empirical linear models based on parallel conductor concept are unable to simulate effective conductivity of a shaly-sand formation saturated with water of low conductivity'. Such a conclusion is actually at odds with the analysis in the body of the paper.

The analysis of the models for the case, where $m = 0$, i.e. 100% porosity, is also in error. Sri Niwas *et al.*[1] state that 'In this case, Glover, Mixing and Bussian equations give σ_0 equal to $(\sigma_s + \sigma_w)$, $\max(\sigma_s, \sigma_w)$ and σ_w respectively. Thus, Bussian equation simulates physics of the situation more realistically.' In fact both the Glover *et al.*[5] and Bussian[2] model give $\sigma_0 = \sigma_w$ for $m \to 0$. The paper's second conclusion is that 'the existing nonlinear equation of Glover *et al.* and the Mixing equation studied by Lima *et al.* are able to simulate the effective conductivity curves for the entire range of water conductivity only for low porosity and these fail to simulate the real behaviour as the porosity increases'. Not only is the conclusion not true because it is based on erroneous interpretation, de

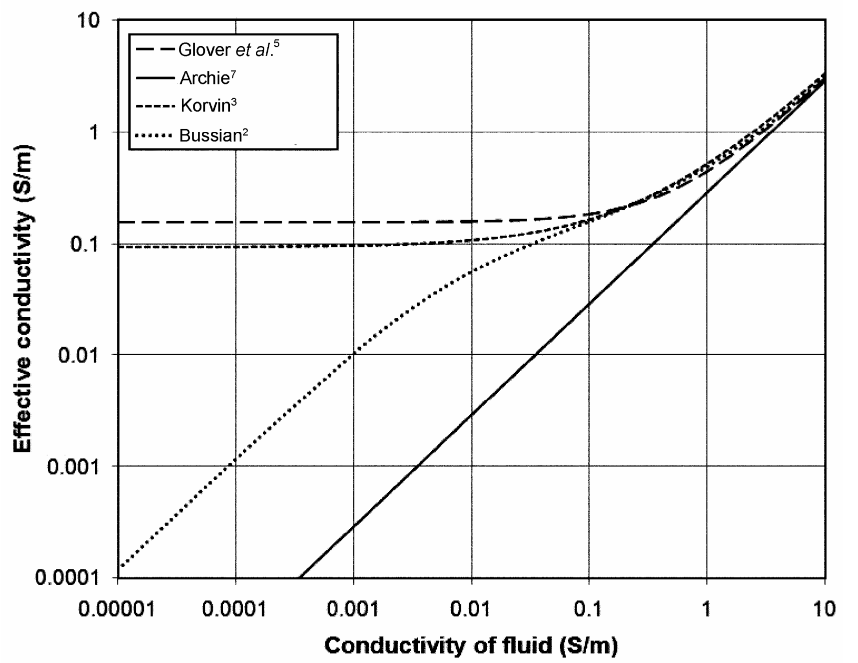

Figure 1. Effective conductivity as a function of fluid conductivity obtained for the four models used by Sri Niwas *et al.*[1], viz. Glover *et al.*[5], Mixing (Korvin[3]), Bussian[2] and Archie[7] for $m = 1.5$, $\phi = 0.439$ and $\sigma_s = 0.22$. These parameters are the same as those in figure 2 panel b in Sri Niwas *et al.*[1]. Axes have been adjusted for the usual range of physical values of a pore fluid.

Lima *et al.*[6] never 'studied' or even mentioned the Glover *et al.*[5] equation. Instead the Glover *et al.*[5] paper was referenced once in the introduction supporting the fact that the traditional Archie's law fails in freshwater reservoirs, which, ironically is a claim that the paper does not make.

The third of the paper's conclusions is that 'The Bussian equation simulates the effective conductivity curves for all ranges of porosity and water conductivity'. Although this would not be considered a particularly revolutionary conclusion, there is no evidence in the paper to support it – that is to say, no experimental data or numerical modelling by the authors or others. Without some recourse to experimental data the paper cannot, in my view, comment on what works and what does not. Experimental data notwithstanding, if one is to examine the behaviour of the models, as Sri Niwas *et al.*[1] have done in their figure 2, there is clear evidence in three of the four panels that the Bussian model is behaving significantly worse than the Korvin[3] or Glover *et al.*[5] models especially at low fluid conductivities, where it takes values that are significantly less than those demanded by the limits imposed by the matrix conductivity. In order to make this clear, I have taken the parameters in figure 2 part b (viz. $m = 1.5$, $\phi = 0.439$, $\sigma_s = 0.22$) and repeated the calculations (Figure 1). Here the classical Archie[7], Korvin[3] and Glover *et al.*[5] models are calculated in a straightforward manner as they are linear, whereas the nonlinear Bussian[2] model is calculated using a conformal mapping technique. This is an elegant method of solving the equation that takes only seven lines of code. We can see that the value of the effective conductivity as $\sigma_w \to 0$ stabilizes at 0.092 S/m and 0.156 S/m for the Korvin[3] and Glover *et al.*[5] models respectively. This indicates that the conductivity is dominated by the fixed matrix component (with a slightly different value provided by each model). In contrast, the bulk conductivity from the Bussian[2] model is still controlled by the conductivity of the fluid, and decreasing with fluid conductivity at the same rate as the classical Archie's law[7].

The fourth of the paper's conclusions is that '. . .the Bussian equation which is more consistent with the physics, reduces to the existing linear models, and thus is consistent with these models. Hence, for nonlinear interpretation of well log data Bussian equation is the most appropriate one'. We have seen that, of the equations mentioned by the authors, the Bussian equation is the only nonlinear one, and while it does reduce to some existing linear models, it does not reduce to those of Glover *et al.*[5] and Korvin[3]. I could not recommend it as the most appropriate one to use in general.

I am led to the conclusion that (i) the conclusions reached by Sri Niwas *et al.*[1] are either erroneous or not supported by evidence, (ii) both the Korvin[3] and Glover *et al*.[5] models do a fairly good job at describing the bulk conductivity of a reservoir rock composed of two conducting phases, and (iii) certain weaknesses exist in the Bussian[2] model. I would recommend that a full and high quality review of all the models available is carried out so that we can really understand the models available to us.

1. Sri Niwas, Gupta, P. K. and de Lima, O. A. L., *Curr. Sci.*, 2007, **92**, 612–617.
2. Bussian, A. E., *Geophysics*, 1983, **48**, 1258–1268.
3. Korvin, J., *Geoexploration*, 1982, **19**, 785–796.
4. Tenchov, G. G., *J. Pet. Sci. Eng.*, 1998, **21**, 263–271.
5. Glover, P. W. J., Hole, M. J. and Pous, J., *Earth Planet. Sci. Lett.*, 2000, **180**, 369–384.
6. Lima, O. A. L., Clennell, M. B., Nery, G. G. and Sri Niwas, *Geophysics*, 2005, **70**, 1–10.
7. Archie, G. E., *Trans. AIME*, 1942, **146**, 54–67.

Received 14 April 2010; accepted 21 June 2010

PAUL W. J. GLOVER

Department of Geology and Engineering Geology,
Université Laval, Québec,
G0A 4E0, Canada
e-mail: paul.glover@ggl.ulaval.ca