Georges Matheron (1930–2000)

Adrian Baddeley
Department of Mathematics & Statistics
University of Western Australia
Nedlands WA 6907
Perth, Australia
adrian@maths.uwa.edu.au

Statistical science has lost one of its most visionary and talented, productive and important, scholarly and incisive, inspiring and humble figures. Professor Georges Matheron, who passed away on 7 August 2000, was for four decades a world leader in the statistics of spatial phenomena.

Matheron was the founder of *Geostatistics* (the application of statistical science to spatial processes in geology); the principal developer of the *Theory of Random Sets* and co-founder of *Mathematical Morphology* (the underpinnings of digital image analysis and spatial statistics); and a leader in studying the *Physics of Random Media,* particularly for porous media. He also made important contributions to the philosophical foundations of statistics, and developed some of the earliest computationally-intensive methods for stochastic simulation. His legacy includes two flourishing schools of research, five books, over 250 papers, and a deep and lasting influence on generations of researchers. Matheron's work has benefited mining engineers, earth scientists, statisticians, physicists, electrical engineers, computer scientists, mathematicians, and all users of digital image analysis.

Strongly motivated by real applications, particularly in mining and hydrology, Matheron was at the same time a mathematician of impeccable scholarship, depth and skill. In each of the four major fields which he developed, Matheron erected strong theoretical foundations, which survive intact today, and also elaborated the practical implications of the theory. For example, his seminal work on random set theory (Matheron, 1975) draws connections between imaging hardware and software, the foundations of stochastic processes, general topology for hyperspaces of closed subsets, and the epistemology of Kant.

Georges Matheron was a graduate of the elite Grandes Ecoles system, through the *Ecole Polytechnique* and *Ecole Normale Supérièure des Mines de Paris*, where he received high-level education both in earth sciences and in mathematical sciences, including probability (for which the great Paul Lévy was his teacher) and physics.

Matheron began his career in 1954 with the French Geological Survey. He became interested in the work of South African geologists (Krige, Sichel and de Wijs) on 'reserve estimation', essentially statistical inference about mineral reserves based on limited spatial observations. Generalising and systematising the South African techniques, Matheron built a complete, coherent theory of modelling and estimation for spatial variables. He coined the name *Geostatistics* in 1962 (defining it as "the application of random function theory to the study of natural phenomena fluctuating in space and/or time") and the term *kriging* for least squares optimal spatial interpolation, in honour of Krige. The entire theory of linear geostatistics was laid out in his epic Treatise of Applied Geostatistics (Matheron, 1962, 1963a) and his PhD thesis (Matheron, 1965), both published in French. Simultaneously an expository article appeared in English (Matheron, 1963b).

Characteristically, Matheron did not rest with the foundation of this new approach, but

energetically and creatively pursued its extension and improvement. The foundations were consolidated in the "theory of regionalised variables" (Matheron, 1965, 1971, 1973). Non-stationary models called "intrinsic random functions" (Matheron, 1973) were developed. Stochastic simulation techniques including conditional simulation were explored (Matheron, 1972; Matheron *et al.*, 1987). Nonlinear estimation methods called "disjunctive kriging" (Matheron, 1976) were inspired by multivariate statistical techniques. Still more general problems of inference and prediction were addressed by the theory of "change of support" (Matheron, 1983).

Matheron's ideas had immediate practical impact in some parts of the mining industry, and were rapidly disseminated in the French scientific community. However, the more widespread recognition of Matheron's work in geostatistics came a decade later. It was assisted by a publication in the Journal of Applied Probability (Matheron, 1973), by a NATO Advanced Study Institute near Rome in 1975, and notably by the efforts of Matheron's students André Journel and Michel David, who moved to North America in the late 1970's (David, 1977; Journel & Huijbregts, 1978).

Around 1964, while consulting for the oil industry, Matheron began to investigate "morphology", the characterisation of geometrical shape, with application to the microstructure of minerals and porous rocks. In collaboration with Professor Jean Serra, he founded *Mathematical Morphology*, a coherent mathematical theory of geometrical operations on (digital or continuous) images (Serra, 1982, 1988) and developed its probabilistic foundations as the *Theory of Random Sets* (Matheron, 1969, 1975). This visionary work addressed both the practical issues of digital image processing (which was still in its infancy at that time) and the mathematical difficulties of building stochastic models for random spatial patterns. These first publications expounded all the essential tools and coined many standard terms, such as 'Boolean model' (Matheron, 1968b). Practical applications and simulation techniques were explored hand-in-hand with the theory. See Matheron and Serra (1998).

Again characteristically, this visionary idea was carried through to its fullest potential. Matheron and Serra jointly oversaw the development of a full analogue of linear filtering theory in the very nonlinear setting of mathematical morphology (Serra, 1988; chapters 3 and 6 by Matheron) and ultimately an algebraic formulation of image analysis in the context of lattice theory (Matheron, 1990, 1996). Again characteristically, these theoretical extensions were conceived with a view to practical applications, and indeed yielded powerful new techniques.

After developing a programme in probability and statistics at the Nancy School of Mines, Matheron joined the staff of the Paris School of Mines, and established the Centre de Morphologie Mathématique (Centre for Mathematical Morphology) at Fontainebleau in 1968. This separated in 1986 into two units, the Centre de Géostatistique directed by Matheron and the Centre de Morphologie Mathématique under Professor Jean Serra. To this day, both units are supported predominantly by industry consulting and research work.

In the late 1960's, Matheron outlined the basis for a general theory of porous media and their hydrodynamic permeability (Matheron, 1967, 1968a). His approach applies to any physical process satisfying a conservation law and linear constitutive equations, such as thermal, electric or elastic propagation. Results included the existence and uniqueness of the (random) solution of the Navier-Stokes equation associated with a random closed set (Matheron, 1979), useful upper bounds for permeability, and geodesics in media with a random refractive index. Hydrological applications were developed (Matheron and De Marsily, 1980).

Epistemology was fundamental to Matheron's thinking in geostatistics and in mathe-

matical morphology. Spatial variables in geostatistics are modelled as realisations of random functions, yet all our data will come from a single realisation of the model. Digital images and spatial patterns may be idealised as subsets of continuous Euclidean space, yet are observed using devices with inherently limited resolution. Matheron wrote an articulate monograph resolving these epistemological questions (Matheron, 1978, 1989) which provides a coherent framework for the 'purely objective' use of probabilistic models in science.

Some individual ideas of Matheron's were of course independently discovered by other scholars, including R. Hardy ("radial basis functions" for gravity data), Y. Ghandin ("objective analysis" in atmospheric science), D.G. Kendall (abstract theory of random sets; Kendall, 1974) and B. Matérn (spatial statistics, especially in forestry). However it would be fair to say that Matheron was unique in combining great mathematical strength with good scientific subject knowledge, a truly interdisciplinary approach, and the ability to work anywhere on the continuum between theory and practice. His many outstanding students attest to his abilities in teaching and fostering young people.

The statistical community owes an enormous debt to this great man.

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RESUME

La contribution scientifique du Professeur Georges Matheron est immense. Il est bien connu comme fondateur de la *géostatistique* (méthodologie stochastique pour les sciences de la terre) dont les applications pratiques actuelles sont innombrable. Avec J. Serra a-t-il également fondé la *morphologie mathématique* (théorie mathématique et pratique des opérations géométriques sur les images). La *théorie des ensembles aléatoires* a été créée par Matheron pour soutenir de façon fondamentale les recherches sur le traitement des images. Matheron a fait des contributions essentielles au *physique des milieux aléatoires*, ainsi que des importants travaux philosophiques sur l'objectivité des methods probabilistes.