GEORG VON NEUMAYER'S LEGACY IN GEOMAGNETISM

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Terrestrial magnetism—its temporal and spatial manifestations and origins—has fascinated humans for 2000 years and has long been exploited for navigation. But not until the 19th and early 20th century was systematic mapping and observation of the field undertaken on a global scale, a satisfactory mathematical theory of magnetism developed, and a dynamo origin in the core identified. Georg von Neumayer was one of the leading luminaries who laid the observational basis for these advances. His principal contributions were in persistent and meticulous observation of earth and space science phenomena, particularly in the southern hemisphere, often carried out under challenging conditions. This talk traces the development to modern times of the areas of geomagnetism where von Neumayer played a pioneering role—establishing a world network of magnetic observatories, mapping and modelling of the geomagnetic field, the quest for the origin of the field, exploration geophysics (diagnostic use of magnetic fields to characterise subsurface bodies and geology), solar-terrestrial effects and auroral physics, magnetic disturbances and a relationship with weather, polar science and more. Perhaps his greatest legacy is in the foundation of a spirit of peaceful scientific collaboration between nations and sharing information for the common good. This is best exemplified by his lead role in the first International Polar Year (1882–1883) and its sequel today—the 4th IPY 2007–2008.

Key words: terrestrial magnetism, geomagnetism, world network of magnetic observatories, exploration geophysics

THE NATURE and origin of the Earth's magnetic field has engaged human curiosity, from the time of the Chinese geomancers more than 2000 years ago, Albert Einstein (1879–1955) recalls:

> A wonder of such nature I experienced as a child of 4 or 5 years, when my father showed me a compass. That this needle behaved in such a determined way did not at all fit into the nature of events, which could find a place in the unconscious world of concepts (effect connected with direct 'touch'). I can still remember … that this experience made a deep and lasting impression upon me. Something deeply hidden had to be behind things. (quoted in Campbell, 2001).

The history of discovery and characterisation of the Earth's magnetic field combines contributions from direct observations, on land, at sea, and in space, with laboratory measurements and improvements in instrumentation. All these have been complemented by mathematical analysis, modelling and computer simulations. Georg Balthasar von Neumayer played a key role in the early part of this history, his greatest impact being in the observational area.

When Edmund Halley produced the first magnetic (declination) map of the Atlantic Ocean in 1700, little was known about the nature and origin of the Earth's magnetic field. Because of its critical importance for navigation, the thirst for further knowledge about the geomagnetic field was insatiable, and governments and their navies were eager to invest in acquiring better information about it in all parts of the globe. This was also an era when scientific and geographical exploration went hand-in-hand. The need for detailed mapping of the magnetic field provided Neumayer with the ideal opportunity to indulge his undoubted passion as a young man for exploration and travel.

An entertaining story, told by Pierre Burton (1988: 533; slightly edited herein for brevity), illustrates both Neumayer's reputation in geomagnetism and his boyish passion for exploration. The story concerns Roald Amundsen, whose meticulous preparations for an expedition to find the North West Passage included learning about the Earth's magnetic field and acquiring observational skills. Amundsen travelled to Munich to accomplish this.

> Late in 1900, Amundsen, virtually penniless, rapped unannounced on the door of the acknowledged expert on terrestrial magnetism, Professor George Neumayer, Director of the German Marine Observatory. Amundsen told the profes-

> sor that to justify further explorations, he must acquire scientific knowledge. Neumayer stared hard at the lanky young Norwegian with the long, morose face: *'Young man',* he said*, 'you have something more on your mind'.* Amundsen mentioned the Northwest Passage. That did not satisfy the professor, '*Ah,.there is still more*'. Finally, Amundsen mentioned studying the North Magnetic Pole. At that Neumayer flung his arms around Amundsen, crying, '*If you do that you will be the benefactor of mankind for ages to come. That is the great adventure*.'

Neumayer took Amundsen under his wing and, over 40 days, spent 250 hours studying the theory and practice of magnetic observations.

MAGNETIC OBSERVATORIES

Geomagnetic observatories monitor continuously the constantly changing magnetic field of the Earth. Short-term changes result predominantly from the sun's influence and have applications such as forecasting solar and space weather, identifying crustal structures, resource exploration and solar–terrestrial research. Long-term changes of the field (called secular variation) are caused by the dynamo action of fluid motions in the Earth's outer core and are important in navigation and research into the internal dynamics of the Earth.

The very first Australian geomagnetic observatory, the Rossbank Observatory (Savours and McConnell 1982), was established by the Royal Society of London in 1840 in the Domain in Hobart (then Hobarton). This was just eight years after the celebrated German scientist and mathematician Carl Friedrich Gauss (1777–1855) built the first 'absolute' observatory in Göttingen in 1832. Installation of instruments at Rossbank was undertaken by James Clark Ross's naval party on their way south to explore Antarctica aboard the *Erebus* and *Terror*. Rossbank operated from 1840 to 1854, when a lack of resources in the young colony forced its closure.

Four years after Rossbank ceased operations, Neumayer established the first geophysical observatory on the Australian mainland—the Flagstaff Observatory for Geophysics, Magnetism and Nautical Science—in Melbourne in the old signal station on Flagstaff Hill. To do that, Neumayer, aided by the authority of Alexander von Humboldt, succeeded in getting the necessary support from King Maximilian II of Bavaria and the government of the Colony of Victoria. Today the site, in what is now Flagstaff Gardens, is a short walk from Melbourne's Central Business District. Surrounded by busy streets, it is a tiny green oasis in the midst of a big city—a far cry from its scientific past. The observatory was a significant milestone in the development of the colony. In the words of Home and Kretzer (1991), 'Its establishment was an event of considerable significance in the scientific and intellectual history of Victoria and, indeed, of the Australian colonies more generally'. Neumayer served as Director of the Observatory from 1857 to 1864, after which he returned to Germany.

The Melbourne observatory was moved in 1862 from its original site in the Flagstaff Gardens to the Botanic Gardens, the geologically more suitable site originally chosen by Neumayer. Subsequent encroachment of electric tramways and railways forced a further move—to Toolangi in 1919 where the observatory operated until 1986, when it was replaced by the Canberra Magnetic Observatory (McGregor 1979).

Magnetic observatories need to be sited in areas of low magnetic-field gradient—both where the observatory buildings are located and in the surrounding region. Neumayer appears to have been the first person to fully appreciate this. The detailed magnetic survey he carried out in preparation for choosing a suitable observatory site in Melbourne set a precedent that has been followed ever since. In his brief survey work carried out in Tasmania in 1864 (Quilty 2007), Neumayer determined that Rossbank was an unsuitable site for an observatory because of the magnetic influence of the nearby basalt (dolerite) columns.

Neumayer's tying of his Victorian and Tasmanian regional magnetic survey observations to Rossbank, and therefore other international sites, was very significant. He knew what he was doing in a global sense and was well aware of the need to determine accurate station differences and the related 'crustal correction' at an observatory—that is, the contribution from the Earth's crust to the undisturbed (non-transient, steady-state) field at an observatory. Today, we go to great lengths to determine station differences, to be used when observatories have to be relocated, and crustal corrections so that observatory data are representative of the Earth's main (core) field.

Geoscience Australia operates the present Australian network of geomagnetic observatories, with six observatories in Australia and three in Antarctica (Hopgood 1993; Hitchman 2007, 2008; Lewis 2005). These provide a wealth of information for purposes ranging from navigation to space weather forecasting. The network's long continuous record owes much to Neumayer's re-establishment of magnetic monitoring in Melbourne following its cessation in Hobart. The Hobart–Melbourne–Toolangi–Canberra sequence has provided over 170 years of magnetic field data in SE Australia (among the longest in the world), while in Western Australia the observatories at Watheroo (established by the Carnegie Institution of Washington) and later at Gnangara have been in operation for over 90 years. Antarctic observatories at Macquarie Island and Mawson began operating in 1952 and 1955, respectively. Other magnetic observatories in northern Australia have been established by Geoscience Australia in the 1980s and 1990s; it is expected that they too will, in time, contribute similarly venerable records of magnetic field variations. All the Australian observatories and their dates of operation are listed in Table 1.

MAGNETIC FIELD SURVEYS

In the 19th and early 20th centuries, the desire for information about the magnetic field over the entire globe was such that any survey data added greatly to the compendium of knowledge. The distinction between magnetic surveys to map the spatial variations of the field (which requires a very dense set of relatively low accuracy observations) and mapping the secular change of the field (which requires a sparse network of very accurate observations) was not deemed important. In the surveys by Neumayer, and continued into the 20th century through the work of the Carnegie Institution of Washington, the technique was to measure the field as accurately as possible at as many stations as possible. Logistical considerations were the limiting factor. It was in this manner that Neumayer conducted his remarkable magnetic survey of the Colony of Victoria between 1858 and 1864.

Magnetic Survey of Victoria, 1858–1864

Georg von Neumayer's enthusiasm for geomagnetism extended to arduous field campaigns by horse and cart throughout Victoria and into New South Wales and South Australia. In all, he accomplished comprehensive observations of declination, inclination, and total field intensity at some 230 stations. This was in addition to meteorological and other measurements. Neumayer's perseverance with extensive magnetic field operations was pioneering—only Humboldt had conducted more remote scientific and survey operations, possibly matched by Hansteen's trek across Russia to the Pacific in about 1828.

Neumayer acknowledged that Edward Sabine was his main influence in starting his magnetic surveys. Sabine, President of the Royal Society and Scientific Adviser to the British Admiralty, was the person who carried on Gauss's and Weber's efforts to establish a world network of magnetic observatories, and was the instigator of the polar expeditions of the *Erebus* and *Terror* and the establishment of the Rossbank Observatory.

The survey of Victoria is described in Morrison (see pages 48-61) and the results are recorded in a splendid volume (Neumayer, 1869) that includes contour maps of the various components of the field. Besides being an important record of the magnetic results of his Victorian survey, Neumayer's book is in itself an important narrative describing the sites and his travels, and it gives a valuable insight into places and people in colonial Victoria. During the leg of the survey conducted in 1862, Neumayer sought artists to accompany him on his exploits and was memorably recorded in the iconic sketches of the Mount Kosciusko area by Eugene von Guérard (Pullin 2011: 128-131)—see http://artsearch.nga.gov.au/Detail-LRG.cfm?IRN=48469&View=LRG

Neumayer's magnetic survey adventures led directly to other great Australian paintings by both von Guérard and Nicholas Chevalier.

Neumayer's survey set the benchmark for subsequent surveys and was not matched in resolution until the mid-20th century. Even the surveys carried out in the Australian region by the Carnegie Institution of Washington's (CIW) Department of Terrestrial Magnetism from the 1920s onwards, though on a much larger geographical scale, had larger spacings between stations. An important difference, however, was that the CIW stations were accurately pin-pointed and marked with permanent markers. This has permitted many of them to be reoccupied up to the present day to determine the secular change of the field (e.g. Barton et al. 1989).

The magnetic survey work carried out by Neumayer spanned the gold rush days in Victoria, but we are not aware that observations were generally used to detect mineral deposits at that time. Neumayer certainly observed over virgin quartz reefs near Mt Hotham during his survey, and the survey clearly identified regions of high and low magnetic field variability reflecting differing crustal geologies. Neumayer's survey results were successfully used for providing accurate compass correction informa-

Table 1. Australian Magnetic Observatories. PPM = Proton Precession Magnetometer; AMO = Automatic Magnetic Observatory; PEM = Photoelectronic magnetograph; EDA = EDA 3-component fluxgate variometer; RCF = Narod Ringcore fluxgate magnetometer; DMI = Danish Meteorological Institute 3-axis fluxgate magnetometer; [1] Hobart, Melbourne, Toolangi & Canberra are a succession. [2] Watheroo was succeeded by Gnangara. [3] Australia provided assistance to the Government of PNG to run this observatory. [4] A variation station (absolute observations made are below observatory standard).

Observatory (lat N,lon E,alt.)	Instrumentation	Duration
Rossbank, Hobart (-42.9° 147.5°)	Observations	Oct 1840 – Dec 1854
Flagstaff, Melbourne (-37.8° 145.0°)	Obs'ns./photog.	1858–1862
Melbourne Botanic Gardens (-37.8° 145.0°)	Obs'ns./photog.	1862 – 1919
Toolangi, VIC (-37.5° 145.5°)	Eschenhagen analog.	1919 – Jan 1939
	LaCour analogue	Jan 1940 – 1986
Canberra[1], ACT (-35.315° 149.363° 859 m)	Elsec AMO digital	1978 – 1995
	RCF/PPM digital	1996 – present
Watheroo[2], WA (-30.3° 115.9°)	Eschenhagen analog.	Jan 1919 – Mar 1959
Gnangara, WA (-31.780° 115.947° 60 m)	Eschenhagen analog.	1957 – 1990
	Elsec AMO digital	1990 – 1993
	EDA/PPM digital	1994 – 1998
	DMI/PPM digital	1998 – 2004
	EDA/PPM digital	2004 – present
Learmonth, WA (-22.222° 114.101° 4 m)	EDA/PPM digital	1987 – Feb 1999
	RCF/PPM digital	Feb 1999 – Aug 2001
	Bartington/PPM	Aug 2001 – Dec 2001
	DMI/PPM digital	Dec 2001 – present
Darwin, NT (-12.4° 130.8°)	Askania analogue	1957–1959 (IGY)
Port Moresby[3], PNG (-9.408° 147.159° 70 m)	LaCour analogue	1958 – Jul 1995
Kakadu, NT (-12.686° 132.472° 14 m)	RCF/PPM digital	Mar 1995 – present
Charters Towers, QLD (-20.090° 146.264° 370 m)	EDA/PPM digital	1983 – Aug 2000
	DMI/PPM digital	Aug 2000 – present
Alice Springs, NT (-23.761° 133.883° 557 m)	RCF/PPM digital	1992 – present
AUSTRALIAN ANTARCTIC TERRITORIES		
Cape Denison, Antarctica (-67.0° 142.7°)	Eschenhagen an'log.	1912 – 1913
Macquarie Is. (-54.5° 158.95° 8 m)	LaCour analogue	1952 – 1985
	PEM/PPM digital	1986 – 1991
	RCF/PPM digital	1992 – present
Heard Island, AAT (-53.0° 73.6°)	LaCour analogue	1952 – 1954
Mawson, Antarctica (-67.604° 62.879° 12 m)	LaCour analogue	1955 – 1986
	PEM/PPM digital	1987 – 1991
	RCF/PPM digital	1992 – present
Wilkes (-66.2° 110.6°)	Ruska analogue	1957 – 1968
Casey (-66.283° 110.533° 40 m)	Direct observations	1975 – 1987
	EDA digital	1988 – 1998 *
		EDA digital 1999 – 2007
	DMI/PPM digital	2007 – present
Davis[4], Antarctica (-68.577° 77.973° 29 m)	Direct observations	1973 – 1985
	EDA digital	1986 – present

tion for SE Australia and for improving the quality of global models and maps of the Earth's magnetic field and its variations.

Modern Magnetic Surveys

The survey work initiated by Neumayer in Australia has been continued and expanded up to the present day but in forms more closely tailored to specific objectives. For mineral exploration, magnetic anomaly information down to a scale of tens of metres is of interest, and for archaeological and geotechnical purposes to a sub-metre level. Aeromagnetic surveys are extensively used for detecting mineral, oil and, more recently, particular environmental or salinity characteristics in the ground. Study of large-scale geological structures requires information at relatively long wavelengths organised so that different survey datasets can be merged. Satellites have become the main platform for such applications. For mapping the field for direction-finding purposes and for geophysical inversion to determine source regimes in the Earth's core, it has been traditional first to measure the secular change of the field. This requires relatively few stations, preferably continuously-recording permanent magnetic observatories. A station spacing of 300–500 km is adequate given that the source of the signal is at a depth of 3000 km. The secular change information can then be used to update costly but high-resolution ground, marine and airborne survey data.

In Australia and the South West Pacific, the spacing between magnetic observatories far exceeds 300 km, so the network is supplemented with *magnetic repeat stations*. At these repeat stations, the field is re-measured accurately every few years to determine the secular variation (Lewis 2008). By the early 1980s, upwards of 50 repeat stations were operated by the Bureau of Mineral Resources (now Geoscience Australia) to provide secular variation data in this way, requiring a major field campaign of ground and air travel every five years. The combined observatory and repeat station network then had an average station separation of about 500 km. Improvements in the number and standard of observatories and the availability of high-quality low Earth-orbiting satellite data have permitted the number of repeat stations to be reduced today to 15. The average spacing in the combined networks is now about 1000 km.

Between 1967 and 1982 a broad nationwide magnetic survey similar to Neumayer's surveys of Victoria, New South Wales and South Australia was carried out by the Bureau of Mineral Resources. The particular goal of this 'third-order' magnetic survey of Australia was to chart features of the regional magnetic field with dimensions 50–100 km (Van der Linden 1970). Magnetic field observations were made roughly every 15 km along navigable roads and tracks, and ships and helicopters were used to reach offshore islands and remote desert regions where no vehicular access was possible. Observers aimed to occupy 50 stations per week. In good conditions 15 stations per day could be occupied. An average station spacing of 35 km was achieved across Australia (McEwin 1982).

Previous limited third-order surveys had measured only the declination (the angle between true north and magnetic north) in Western Australia in 1962, South Australia and New South Wales in 1963, and in New South Wales, Queensland and Tasmania in 1964. This national survey was the first to measure sufficient field elements (declination D, horizontal intensity H, and total intensity F) for the full vector field to be retrieved.

The intention was to cover the country with a 'one-off' third-order survey to supplement the periodic repeat station occupations. A network of repeat stations had been established to provide accurate secular variation data. The third-order survey provided closely spaced results of sufficient accuracy to give fine control over the isomagnetic lines and to indicate how representative of the region the repeat station results were.

For many crustal structure studies and resource-related applications, information about the total magnetic intensity is sufficient. In recent years, Geoscience Australia has levelled and merged the available aeromagnetic data to obtain a high-resolution magnetic anomaly map of the entire continent. Figure 4 shows the 5th edition of the magnetic anomaly map (Milligan et al. 2010).

EXPLORATION GEOPHYSICS

The gold rush in Australia commenced in 1851, and Neumayer was well aware of the potential of magnetic field anomalies both for identifying mineral deposits and for characterising the regolith. He used these arguments in his classic letter to Haines (15 June 1857) seeking support from the Victorian Government for the Survey of Victoria: 'By a Magnetic Map of a country we can draw a conclusion as to its probable value for agricultural and mining purposes....' (Neumayer: 1857). In many ways, the vision of Neumayer, then aged 31, is his legacy. He anticipated the potential of geological or magnetic surveys and his vision has come true. He certainly expanded on the pioneering regional work of Humboldt and on that of his early mentor Johann von Lamont in Germany.

Neumayer's one-day magnetic survey underground in Ballarat was possibly the first documented minerals geophysical exploration in Australia, although some Cornish miners may very well have brought electrical (self-potential) methods to South Australia before Neumayer. His sadly undocumented but detailed magnetic measurements across some quartz reefs near Mt Hotham in November–December 1862 were again pioneering.

Better known is Neumayer's study of the main Cranbourne meteorite in Victoria in 1861 and 1862 (Neumayer 1869; described in Morrison 2004), which appears to be, in Australia, the first use of magnetism in an interpretation of a buried object or mineral deposit. Neumayer's simple and innovative 1861 calculations of the dimensions and depth of the buried meteorite is without doubt a benchmark in geophysics—certainly exploration geophysics. His interpretation was much more than just an Australian first: it is the earliest identified quantitative geophysical interpretation (calculation of dimension, volume and depth to source) anywhere. This is a big call, but for many years Morrison has searched the literature thoroughly without finding anything even nearly similar, until the 20th century. It is possible, even likely, that Neumayer's teacher, Johann Lamont, could have implanted such knowledge into the brain of the young Georg and it is possible classroom or manuscript studies exist, but considerable research has not found any evidence of that. Neumayer's narrative describing the buried meteorite's magnetic character predates by about 18 years the first published text on applying magnetism in the search for mineral deposits (iron ore) by Robert Thalén (1879).

MODELLING

The early isomagnetic charts, commencing with Halley's 1700 declination map of the Atlantic Ocean and 1701 map of the world, were contoured by hand. The method, though in some instances subjective, is simple and readily accommodates large variations in information density and was the method that Neumayer used for his charts of Victoria. Even until the latter part of the 20th century, hand-contouring remained the preferred method for drawing national and regional-scale charts.

Gauss's introduction of the spherical harmonic method for describing the Earth's magnetic field (Gauss 1838) marked a leap forward in our ability to synthesise observational data over the globe into a coherent mathematical model useful for interpolation and extrapolation. The observational data available, and computational problems, limited Gauss's original analysis to degree and order 4 over a spherical Earth. (Gauss actually used 84 data points, read from global charts of declination, inclination and total intensity.)

The massive accumulation of magnetic data from around the world since 1839 allowed Neumayer, H. Fritsche, Edward Sabine and others to enlarge on Gauss's spherical harmonic models of the field calculations. Whereas Gauss had to restrict his calculations to a spherical Earth, the German geophysicist Adolf Schmidt (1860–1944) had adequate data to consider a spheroidal Earth (Chapman and Bartels 1940, Chapters 17 and 18). After his return to Germany, Neumayer used these new techniques to produce better global charts of the Earth's magnetic field. Figure 5 shows Neumayer's total magnetic intensity (magnetic field strength) map of the world for 1885.

The magnetic secular variation information derived from the present-day geomagnetic observatory and repeat station network is the primary data source for the prospective secular variation model in the Australian Geomagnetic Reference Field (AGRF) model and the spherical harmonic secular variation model of the Australian region from 1960 onwards. The AGRF is a spherical cap harmonic model of the geomagnetic field in the Australian Region which is updated every five years. The AGRF model is used widely as a source of information on the geomagnetic field in the region and is particularly useful for applications involving compass navigation and direction finding, mineral exploration and research. The repeat station data are also submitted to international data centres, from which they are freely available.

MENTORING, COLLABORATION AND SHARING

Neumayer benefited greatly from the guidance and support he received from luminaries of his day—Humboldt and Lamont, in particular. He, in turn, selflessly gave of his time and energy in mentoring others; this too must be included as part of his legacy. An outstanding example is the help he gave Burke and Wills at the start of their fateful crossing of Australia from south to north. The young W.J. Wills was one of Neumayer's assistants, given leave to participate in the expedition. Neumayer worked for the organising committee, provided advice and training, and also accompanied the expedition from the River Murray to the Darling River, making geomagnetic measurements. Further examples are the assistance with instruments and training he gave to Fridjof Nansen for his great expedition to the North Pole, and also to Amundsen as described earlier in this article.

Neumayer was also a firm believer in the principle of international cooperation and open sharing of data for the mutual benefit of all. His commitment to working in Australia bears this out. He went to great lengths to ensure that his data and magnetic field charts were adequately published. Perhaps the best example of his efforts to promote international collaboration in science was his role in chairing the International Polar Year Commission and initiating the first International Polar Year (Krause, see pages 95-115), the first of a series of IPYs, culminating in the recent IPY 2007–2008.

This tradition of cooperation and sharing has put us in a good position. It is now axiomatic that magnetic field data collected by nations around the world are made freely available. Australian data, for example, are available through http://www.ga.gov.au/earth-monitoring/geomagnetism.html.

CONCLUSION

Terrestrial magnetism, and its temporal and spatial manifestations and origins, has fascinated humans for 2000 years, and has long been exploited for navigation. But not until the 19th and early 20th centuries was systematic mapping and observation of the field undertaken on a global scale, a satisfactory mathematical theory of magnetism and electricity developed, and a dynamo origin in the core identified. Georg von Neumayer was one of the leading luminaries who laid the observational basis for these advances. His principal contributions were in persistent and meticulous observation of Earth- and space-science phenomena, particularly in the Southern Hemisphere, often carried out under challenging conditions. Neumayer played a pioneering role in establishing a world network of magnetic observatories, mapping and modelling of the geomagnetic field, the quest for the origin of the field, exploration geophysics (diagnostic use of magnetic fields to characterise subsurface bodies and geology), solar–terrestrial effects (auroral physics, magnetic disturbances and a relationship with weather), and polar science. Perhaps his greatest legacy is in the foundation of a spirit of peaceful scientific collaboration between nations and sharing of information for the common good. This is best exemplified by his lead role in the first International Polar Year (1882–1883). Neumayer followed in Humboldt's shoes, as did many others, and he pursued the high standards of acquisition set by his mentor Johann von Lamont. He can rightfully be credited with the initiation of exploration geophysics in Australia. Now that satellites are capable of mapping the global field rapidly in both space and time with greater and greater accuracy, the need to traverse the wild bush of Australia with horse and cart and on foot has disappeared.

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