process has a potential since it requires a pressure of 10^6 atm to achieve similar performance under otherwise identical conditions assuming chemical equilibrium is reached.

The heart of the new process is a solid-state proton conducting ceramic membrane made of strontia–ceria–ytterbia (SCY) perovskite of the form $SrCe_{0.95}Yb_{0.05}O_3$. Porous polycrystalline films of palladium are deposited on either side of the membrane. Palladium (on the anodic end) catalyses the oxidation of H_2 to protons, and are transported across the ceramic proton conductor towards the cathode under the influence of an applied electrochemical potential gradient, where they react with N_2, once again with the aid of the catalytic action of palladium, to form NH_3.

$$3H_2 \rightarrow 6H^+ + 6e$$

$$N_2 + 6H^+ + 6e \rightarrow 2NH_3 .$$

The surface roughness of the palladium electrodes is very large, of the order of 60, and this plays an important role in the production of large quantity of protons that are transported across the conducting membrane. The whole device can therefore be represented by an electrochemical cell: H_2, Pd | SCY | Pd, N_2, NH_3, He. (Nitrogen is supplied in a mixture with helium.) The proton conducting oxide, strontia–ceria–ytterbia, is a solid solution based on pervoskite type $SrCeO_3$ in which 5% of Ce are replaced by Yb. These ceramics are unique in the sense that they have no protons as a host component but incorporate protons via reactions with the atmosphere. In these oxides, doping by aliovalent cations is indispensable for the appearance of proton conduction. Moreover, the working conditions of this electrochemical process ensure a rather high transference number, close to unity, for protons. But a word of caution regarding the concentration of protons is to be added. The concentration of protons in this mixed oxide is high at the reported temperature of 570°C and drops abruptly as the temperature is increased. This limits the temperature of operation to be around 600°C. However, increased rates of formation of NH_3 have been achieved with increased current densities. The cell is heated to 570°C and under such high temperatures, NH_3 does decompose in the gas phase. Though the cell has been designed to keep only the membrane hot, it is unavoidable that the exit stream of gases containing NH_3 is also heated. As a result, Marnellos and Stoukides estimate that up to a maximum of 20% of the NH_3 that has formed at the cathode might have decomposed back into N_2 and H_2. Thus, there is scope for improvement.

One natural question that occurs is how this process crosses over the bar established by thermodynamic equilibrium. The answer lies in the irreversible nature of this process, where the reaction is being driven by electrical energy supplied from outside. It is the separation of the oxidation and reduction processes by the membrane that creates scope for this.

Concept to commercialization is fraught with many difficulties. The mechanisms involved in the new process are yet to be identified and process optimization is still far away. In the end, several issues such as the proton concentration, the cost of the catalyst and power will determine the final fate of this promising new process.

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Geological findings on some postulated synchronous impact-craters on earth

A. V. Sankaran

Our planet earth, throughout its long period of evolution, has been subject to bombardment by meteorites, asteroids, comets and other objects varying from dust to kilometer dimensions. While in the earlier half of this century earth scientists were interested in them for their potential to throw light on the composition of earth, particularly about its interior, their attention during the past couple of decades had shifted to assessing the destructive potential and roles in shaping earthly events like volcanic eruptions, periodic magnetic reversals, mass extinctions, climatic changes and even origins of life. Now, two spectacular impact events – one from the geological past and the other that took place in our present times, hardly five years ago, have aroused the interest of scientists on the earth-impacting objects further. The former is the well-publicized crash of an asteroid 65 million years ago, which scientists attributed as the cause for global climatic changes and extinction of several species of life on earth at that time. This unearthly cause for the mass extinction, never advanced till 1980, jolted many of the contemporary researchers. Fettered, as they were, in their conviction in the principle of uniformitarianism (gradual or step by step transition) operating in evolutionary changes, it was a revelation to them how sudden or catastrophic events, like a meteorite crash can also shape evolution on earth and how sudden disappearance of species need not be ascribed to gaps in the fossil records as many of them had done before. The urge for global search was redoubled in the wake of the second event – the spectacular crash of Shoemaker-Levy9 (SL9) comet, the fragmented parts of which fell one after another over a period of six days on the surface of Jupiter in July 1994, carving a line of multiple craters.

The awareness to the potentialities of such extra-terrestrial agents to influence earth's geology, climate, ecology and evolution of life set researchers of diverse disciplines to catalogue similar crashes that must have taken place, particularly during the earth's early stages of evolution, when the planet is known to have been battered by meteorites and asteroids[1]. However, the global search for probable impact sites is a difficult task to achieve owing to the ever-active geological processes like tectonism, crustal subductions, weathering and erosion which all tend to mask or wipe out typical features of the craters. Except for a few, clearly preserving their original circular shapes and impact generated mineralogy, many others are today hidden by younger formations though, occasionally, these hidden craters have also come to light while carrying out drilling operations or in the course of geophysical and satellite surveys.

The efforts to locate crater chain on earth have, over the past few years, yielded a few possible candidates. Among these, the strongly favoured ones are the three circular structures aligned on a line in Chad, Africa[2] (detected by space shuttle photography), a string of eight in USA[3,4], and five stretched over North America and Europe[5]. However, only two among these crater chains have, so far, received considerable attention. The first proposed by Michael Rampino and Tyler Volk (New York University), are eight crater-like formations in USA, ranging in size from 3 to 17 km and extending for 700 km over a 15 km wide belt in the states of Kansas, Missouri and Illinois (Figure 1). These circular craters exhibit intense geological deformation, radial symmetry, central uplift with outward directed folds, radial and concentric faulting and intense brecciation[2]. While two of these chain members, Decauturville and Crooked Creek, both in Missouri (Figure 1) are undoubtedly impact craters, such an origin for the other six is disputed although they preserve characteristic shock-induced deformation in the form of quartz with planar features, devitrified glasses, spherulitic structures and intrusive breccia dikes.

Rampino and Volk used the two undoubted craters, Decauterville and Crooked Creek, to define a line and project it further east and west and calculate the probability of the rest of the members of this chain falling on this extended line. Their exercise indicated that the rest of the chain members were aligned on this line and this convinced them to conclude that their alignment is unlikely to be accidental. They, therefore, postulated that the craters were created by multiple impacts from disrupted parts of a several kilometers wide asteroid or comet (bolide), their disruption brought about by terrestrial or lunar tidal forces. Their calculations indicated that these dismembered parts were travelling with a velocity of 29.8 km/s and were possibly only a few seconds apart producing earthly impact separation of ~ 45 to ~ 240 km over ~ 1700 km length. This synchronous impact origin has now been questioned by John Luczaj (Johns Hopkins University, Baltimore), who on the basis of published geochronological data, showed that contrary to similar ages that one would expect for these craters, they ranged between 500 and 100 million years. Hence, he believed that these craters must be of volcanic origin, as many others also consider them to be, and that their straight-line alignment is the result of tectonic control exercised by deep fractures in the crust[6]. Rampino and Volk, however, do not agree, as they are not sure of the ages quoted from published literature.

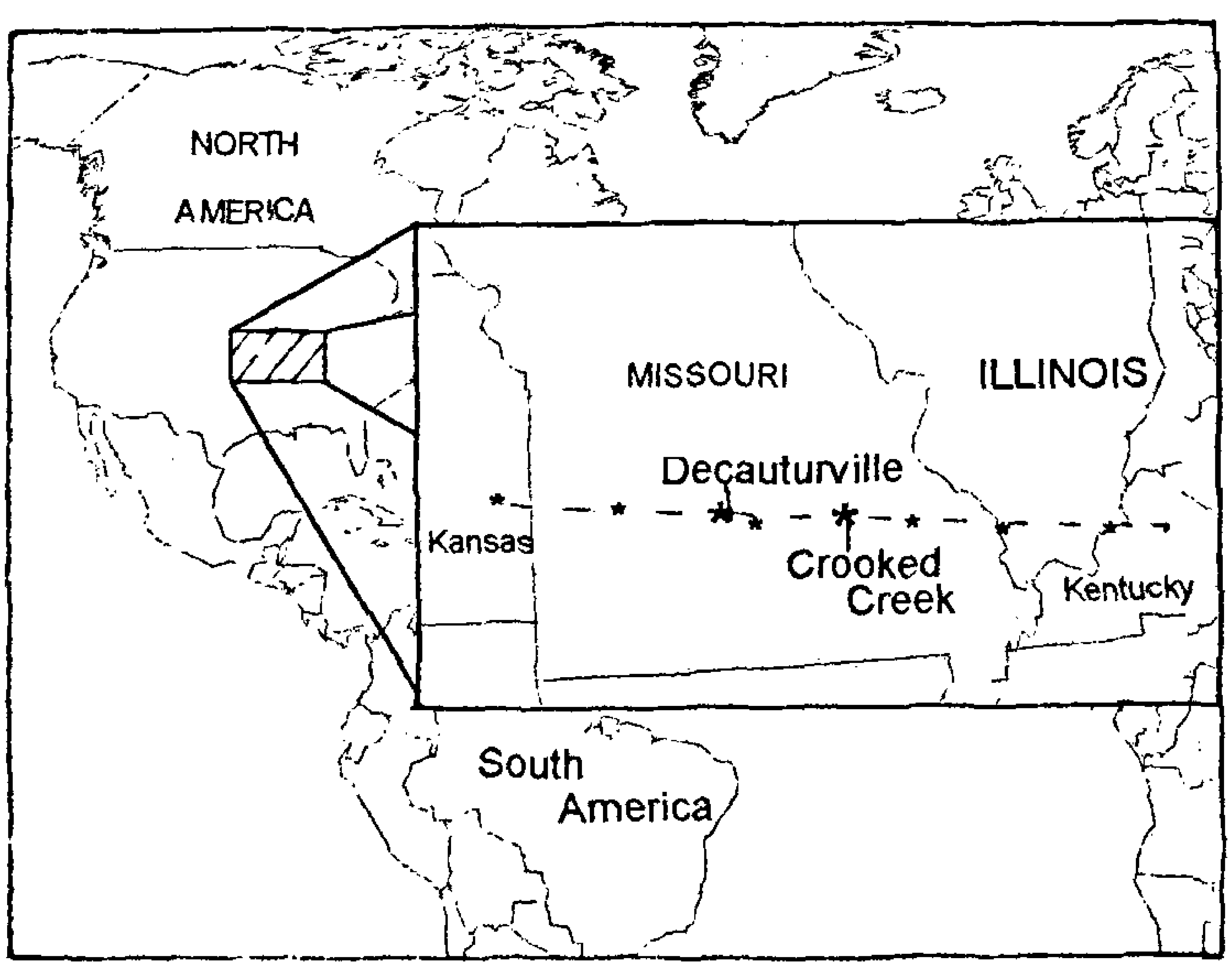

Figure 1. Crater chain believed to be of multiple impact origin stretching for 700 km in Kansas, Missouri and Illinois (USA) over a 15 km width (adapted from ref. 3).

The second much discussed crater chain on earth is the five-membered one distributed in North America and Europe (Figure 2 *a*). This chain is believed to be produced by synchronous multiple impacts, at intervals of few hours, during the Triassic period, 215 million years ago. Though their present distribution is misaligned, when the respective continental plates are moved back to the time of their impact in Triassic period and the crater positions re-plotted, they are found to fall on a line. This interesting finding is the culmination to a serendipitous discovery by John G. Spray (University of New Brunswick, Canada)[5], while studying the Rochechouart crater in France in 1994. This is a 25-km wide, partly eroded crater in the Hercynian rocks of Massif Central. Spray had collected a chip of pseudotachylite (glassy impact-melted rock) and had it dated by $^{40}Ar/^{39}Ar$ laser spot fusion technique which yielded an age of 214 ± 8 m.y. (ref. 5). It struck him that this age coincided with that of the huge ~ 100 km wide Manicouagan crater in Quebec, Canada, dated to be 214 ± 1 m.y. old (determined by high precision U–Pb dating of zircons from the > 200 m thick impact-melt material) and this coincidence prompted him to search for more craters of the same age from among the 150 or so terrestrially impacted craters[7]. His efforts yielded three more craters: (i) a ~ 40 km wide Saint Martin crater in northwest Winnipeg, Manitoba, Canada, presently not clearly exposed but detected by gravity and magnetic surveys and dated to be around 219 ± 32 m.y. old (Rb/Sr dating of impact-melt material); (ii) ~ 9 km wide Red Wing crater in North

Dakota, USA, which is an impact crater on Silurian and Triassic age carbonate formations, but now lying buried below ~ 1.5 km thick Jurassic and younger sediments. This impact event is dated to be 200 ± 25 m.y. old (stratigraphically constrained age); and (iii) a ~ 15 km wide crater at Obolon', Ukraine, buried by 15–300 m post-impact Jurassic and younger rocks. This crater, detected during geophysical and drilling operations, is reported to have impacted around 215 ± 25 m.y. ago. Spray *et al.* found that each of these five structures had features characteristic of hypervelocity impacts giving rise to impact-generated melt sheets (< 10 m thick), shallow cones, minerals showing planar deformation, high pressure polymorphs, diaplectic glasses and central peak basins.

Impressed by their identical ages, Spray, along with plate tectonic researcher David Rowley (University of Chicago), replotted these crater sites on the tectonic reconstruction of North American (Laurentian) and Eurasian plates for the 214 million year period, the time when the multiple crashes were supposed to have occurred. Surprisingly, the Manicouagan, Rochechouart and Saint Martin craters fell equidistant, almost perfectly on a line (Figure 2 *b*). Besides, they were also on the same palaeolatitude of 22.8°N (within 1.2°, ~ 110 km), paralleling the equator and stretched over palaeolongitude of 43.5° or 4462 km. This is considered a good fit to a small circle path about the earth's spin axis. Though the relatively smaller craters, Obolon' and Red Wing, located respectively at the eastern and western extremities of the chain are not in the general alignment, the authors found that they lay on a great circle (declination of 37.2°) having identical trajectories with respect to latitude parallel trajectory of the three bigger ones, namely Red Wing and Saint Martin on the eastern end and Rochechouart and Obolon' on the western end (Figure 2 *b*). While the Saint Martin, Manicouagan and Rochechouart craters are believed to be generated by projectiles co-axial with respect to each other, spatial relations of the projectile that carved Obolon' and Red Wing are not clear; according to the authors, Red Wing probably could have been produced by a smaller projectile from the Saint Martin projectile.

As for the nature of the projectile, Spray *et al.* are not sure if it was a comet or an asteroid, as the available geochemical and impact structure studies are not conclusive about this. In tune with obsession of geologists to look for a mass extinction event with every bolide impact or *vice versa*, the authors have pointed out the minor extinction events that have been recorded around the post-impact period, but feel that biostratigraphic and radiometric correlations in this context require more careful study.

The temporal association of these five craters has drawn criticism on the basis of observations in geochronology, palaeomagnetism and planetary physics. There is a strong view that the dating precision of a few million years achieved by the present techniques is inadequate and unless a precision down to a few weeks or days is achieved, some skeptics doubt the synchronous multiple impact origin for the five craters. But, Spray *et al.* argue that temporal constraints provide by radiometric dating alone cannot prov synchronicity of the impacts due t experimental uncertainties. The critica test for synchronous impact remains spatial one[5].

Dennis Kent (Lamont–Doherty Eart Observatory, Columbia University, Ne York) opposes the synchronous impac view of Spray *et al.* after critical exami nation of the published data about th palaeomagnetism in the crater-site sam ples. These data enable one to reconstruc the earth's magnetic field during a par ticular geologic period. This stud involves identifying the orientation of iro minerals that lock themselves in the pre vailing N–S direction while they con gealed from their parent melt formed a that period. According to Kent, data o the remnant magnetization of the mag netic minerals at Manicouagan an

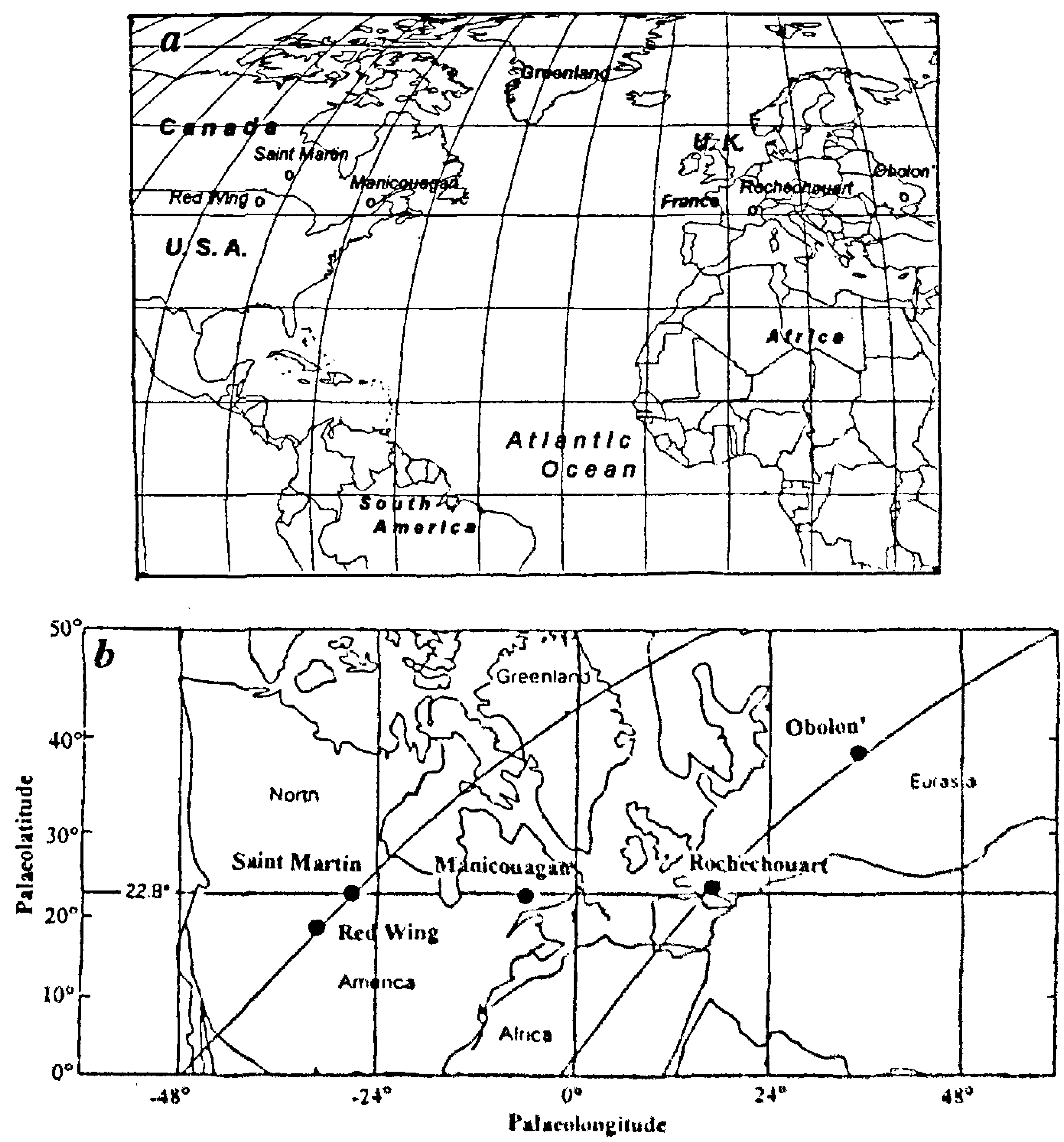

Figure 2. *a*, Present day location of five impact craters postulated to be of synchronous impact origin 214 million years ago during the Triassic period; *b*, Positions of the five craters on a tectonic reconstruction of North American and Eurasian Plates for the Triassic period (adapted from ref. 5).

Rochechouart craters indicate formation in late Triassic palaeomagnetic dipolar field of normal polarity at the Manicouagan but reverse polarity at Rochechouart[8]. This feature revealed by the magnetic minerals at the two sites, according to Kent, indicates an incidence of geomagnetic reversal which implies that the two impact events must have been separated at least by a few thousand years it takes for geomagnetic polarity reversal to take place; and such reversals during the Triassic times have been known to occur about twice per million years[9]. Spray, however, is not convinced by the palaeomagnetic data and feels that the samples for the magnetic studies were drawn from the crystalline rock material and not from the glassy melt[10]. In the former, the magnetic mineral phase develops only when the mineral passes through the Curie point (the temperature at which iron minerals assume magnetic order), a point that an ~ 200–500 m thick body like Manicouagan superheated melt can attain only after tens of thousand years of slow cooling to generate crystalline structure and magnetic order. Consequently, Spray claims that although both Manicouagan and Rochechouart could have formed within a few hours of each other, the resulting impact generated rocks would have reached Curie points at times sufficiently different to allow for a natural geomagnetic reversal to have taken place, accounting for different polarities of these impact structures[10].

Planetary scientists also disbelieve that earth's weak gravity could have captured a comet or asteroid and disrupted it in the manner Jupiter's strong gravity did (Jupiter–Earth difference in mass being over 1–300) when it broke SL9 into several fragments and later drew them on to its surface[11]. An alternate explanation put forward by some envisages that a comet or asteroid is first fragmented during a grazing impact over the earth's atmosphere and subsequently captured in the earth's orbit only to be pulled down on to its surface during its next pass-by[12,13]. However, break-up or fragmentation processes, theorists feel, usually bring about crater clusters and not linear chains, except occasionally as secondaries to large impact events. Though possibilities for multiple impacts over primeval earth do exist, their unlikely survival overcoming destructive geological processes and remaining exposed uncovered by younger formations during the intervening long time span, poses difficulties in their recognition today. Secondly, the critical test for the synchronicity of craters, no doubt, requires that they exhibit similar ages, but whether the narrow precision required for this purpose, overcoming the uncertainties inherent in the isotopic dating technique for attaining this high precision is achievable, is a big question. It appears that, for the present, as Spray *et al.* have expressed, spatial alignment of craters remains a reasonable test for advancing synchronous origin, unless disproved by other studies.

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COMMENTARY

Why, in the present day world, the difficult is easy and the easy almost impossible?*

Yash Pal

Without being too complacent about what scientists in Space, Atomic energy, Defence and Agriculture have been able to do during last few decades, one will have to agree that it is substantial and would do credit to any industrial society of the last few decades of this century. Nonetheless one will have to confess that India has come nowhere close to what we had dreamed of at the time of our Independence. When I say 'we' I mean people my age who had started working soon after the country became independent. Half our population was never in school. The country has suffered serious environmental degradation, our towns and streets are filthy, many do not have safe drinking water, sanitation facilities are almost non-existent in much of the country, regional and religious disputes and also those based on language and caste have become more vitriolic, crime has increased and population growth has not been checked in many parts of the country.

What I have said about our country is in some measure true of the whole globe. Without going into the state of affairs in many parts of Asia and Africa, it is hard for me to reconcile with the fact that people who went to the moon decades ago, those who have been involved in some of the greatest scientific and technological adventures and accomplishments of this era, belong to the same species who would kill off hundreds of innocent

*Based on a lecture given on the 26th anniversary of ISAC.