(1 × 1 km) images of visible reflectance and infrared brightness temperature from a companion instrument ATSR-2, to estimate cloud fraction, cloud-top height and other cloud and surface parameters. □

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Evidence for a late Triassic multiple impact event on Earth

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Evidence for the collision of fragmented comets or asteroids with some of the larger (jovian) planets and their moons is now well established following the dramatic impact of the disrupted comet Shoemaker–Levy 9 with Jupiter in 1994 (ref. 1). Collisions by fragmented objects result in multiple impacts that can lead to the formation of linear crater chains, or catenae, on planetary surfaces[2]. Here we present evidence for a multiple impact event that occurred on Earth. Five terrestrial impact structures have been found to possess comparable ages (~214 Myr), coincident with the Norian stage of the Triassic period. These craters are Rochechouart (France), Manicouagan and Saint Martin (Canada), Obolon' (Ukraine) and Red Wing (USA). When these impact structures are plotted on a tectonic reconstruction of the North American and Eurasian plates for 214 Myr before present, the three largest structures (Rochechouart, Manicouagan and Saint Martin) are co-latitudinal at 22.8° (within 1.2°, ~110 km), and span 43.5° of palaeolongitude. These structures may thus represent the remains of a crater chain at least 4,462 km long. The Obolon' and Red Wing craters, on the other hand, lie on great circles of identical declination with Rochechouart and Saint Martin, respectively. We therefore suggest that the five impact structures were formed at the same time (within hours) during a multiple impact event caused by a fragmented comet or asteroid colliding with Earth.

Approximately 150 impact structures are now known on Earth, most of which are <200 Myr old[3]. They represent a small portion of what would have been a much larger number, most structures having been buried or destroyed via the tectonic and erosional activities of our dynamic planet. The discoveries of an iridium-enriched clay layer[4] and the 65-Myr-old Chicxulub impact structure in Yucatán, Mexico[5], both coincident with the Cretaceous/Tertiary (K/T) boundary, have drawn attention to the global environmental damage such impacts can cause and, hence, their association with mass extinction[6]. Geologists have tended to seek single giant impact structures as potential sources of catastrophe on Earth, but the temporal and spatial association of five impact structures described here indicates that the effects of synchronous multiple impact events produced by fragmented comets or asteroids should not be discounted.

The Rochechouart impact structure in France occurs within Hercynian target rocks of the Massif Central. The structure is partly eroded and no impact-related topography remains. A thin (<10 m) impact melt sheet is overlain by a fallback sequence 20–50 m thick, and underlain by allochthonous and autochthonous basal breccias. A shock zoning study and the distribution of various impact lithologies indicate that the structure is ~25 km in diameter[7]. Previous radiometric work has yielded ages of 154–173 Myr (K–Ar)[8] and 186 Myr (Rb–Sr)[9], but the recent $^{40}Ar/^{39}Ar$ laser spot fusion dating of pseudotachylyte generated in impact-related basement faults has yielded[10] 214 ± 8 Myr (2σ). This revised age is in keeping with the regional geological setting of the structure, whereas the younger age determinations, which implied a Jurassic origin, are now considered to indicate the timing of subsequent Ar loss and Rb and Sr mobilization. The Manicouagan impact structure in eastern Canada is ~100 km in diameter. The target consists of amphibolite to granulite facies metamorphic rocks and anorthosites of Grenville age (~1 Gyr) with overlying Ordovician carbonates. The anorthositic rocks have been locally shocked to yield diaplectic plagioclase glass (maskelynite)[11]. High precision U–Pb

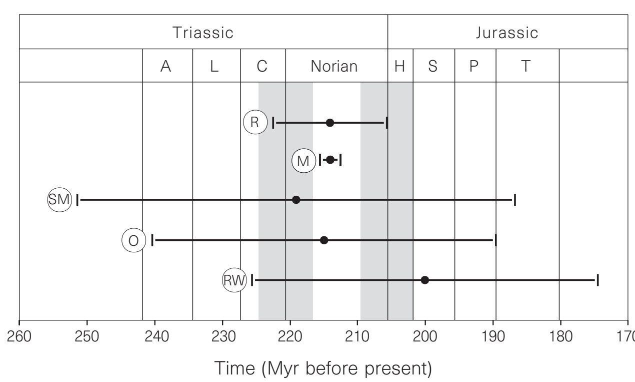


Figure 1 Radiometric and biostratigraphic age data for the five impact structures plotted for the late Triassic to early Jurassic using the timescale of Gradstein *et al.*[22]. Abbreviations for stages as follows: A, Anisian; L, Ladinian; C, Carnian; H, Hettangian; S, Sinemurian; P, Pliensbachian; T, Toarcian. (Rhaetian substage included in the Norian.) Shaded columns show errors for the Carnian/Norian (±4.4 Myr) and Norian/Hettangian (±4 Myr) boundaries[22]. Letter abbreviations for the impact structures (given in circles) as follows: R, Rochechouart; M, Manicouagan; SM, Saint Martin; O, Obolon'; RW, Red Wing.

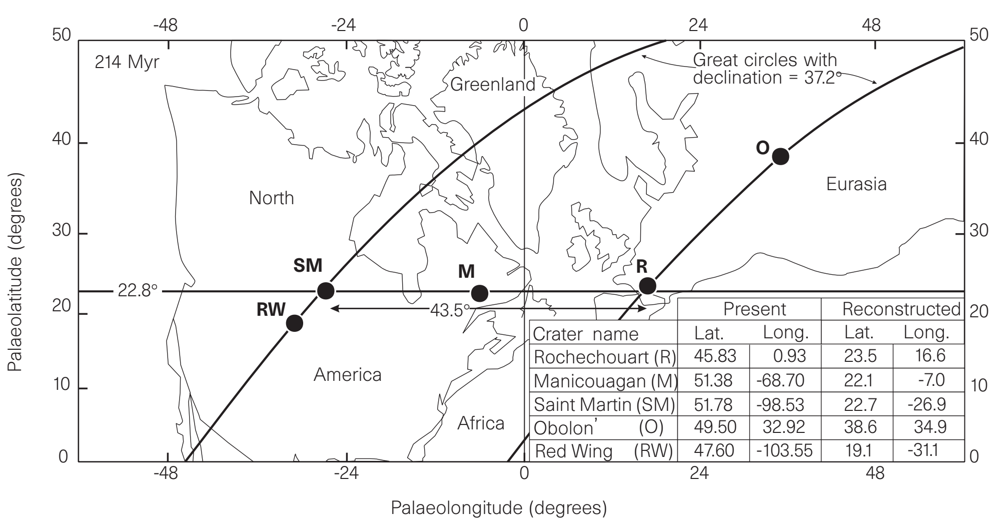
dating of zircons from the >200-m-thick impact melt sheet yields[12] an age of 214 ± 1 Myr (2σ). The Saint Martin impact structure in western Canada is not well exposed, but gravity and magnetic surveys, coupled with the results of a drilling programme in the late 1960s, have revealed its essential structure. It is ~40 km in diameter[13]. The target rocks comprise Superior Province (Archaean) granitic gneisses and overlying Palaeozoic sedimentary cover. The youngest pre-impact material is Devonian, while Jurassic red beds and evaporites constitute the oldest post-impact cover. Rb/Sr dating of the impact melt sheet yields[14] an age of 219 ± 32 Myr (2σ). The Obolon' impact structure of the Ukraine is ~15 km in diameter and buried by 150–300 m of post-impact Middle Jurassic to Quaternary sedimentary rocks[15]. Geophysical and bore-hole data indicate that the target lithologies are early Proterozoic migmatitic gneisses and granitoids, overlain by a mid-Carboniferous to Lower Triassic sedimentary cover. Shatter cones, melt-bonded breccias, diaplectic glass and the presence of coesite[16], microdiamonds[17] and planar deformation features in quartz[15] have been identified from drill core. No radiometric constraints are available for Obolon', but stratigraphic evidence supports a formation age[18] of 215 ± 25 Myr. The Red Wing impact structure of the western USA is ~9 km in diameter and buried by ~1.5 km of Jurassic to Neogene post-impact sediments. The impact structure is formed in Silurian to Triassic carbonates, minor sandstones and evaporites, and provides the structural trap to one of the most prolific oil fields in the United States[19]. It has a stratigraphically constrained age[20] of 200 ± 25 Myr.

Each of the five structures shows features characteristic of hypervelocity impact, including most of the following: impact-generated melt sheets of crustal bulk composition, shatter cones, planar deformation features in minerals, high-pressure polymorphs and diaplectic glasses. All are complex craters and are probably central peak basins[21], though Manicouagan may be large enough to be a peak-ring or multi-ring basin. Based on the timescale of Gradstein *et al.*[22], four of the five impact structures have ages that fall within the Norian stage of the late Triassic, while Red Wing overlaps with the Norian within error (Fig. 1). However, given the possibility of the impacts coinciding to within a few hours, temporal constraints provided by radiometric dating alone cannot prove the synchroneity of the impacts due to experimental uncertainties. The critical test for synchronous impact remains a spatial one.

Using the two best-dated structures as an age constraint (Rochechouart and Manicouagan), the five sites have been plotted on a map showing the reconstructed positions of the North American and Eurasian plates 214 Myr ago[23] (Fig. 2). The three largest impact structures (Rochechouart, Manicouagan and Saint Martin) plot as co-latitudinal at a mean palaeolatitude of 22.8°, and a latitudinal width of ~1.2°. This is a remarkably good fit to a small-circle path about the Earth's spin axis. The spread in palaeolongitude is 43.5° (4,462 km). The three aligned structures thus form a crater chain, or catena, like the catenae described on Jupiter's moons[2]. The probability of the three co-latitudinal structures representing a random event was assessed using Monte Carlo simulation. The probability ranges in a nonlinear fashion from $P \approx 0.0003$ to $P \approx 0.083$ for $N = 3$ to $N = 13$, where N is the total number of coeval impactors. These probabilities decrease by a factor of about 10 if the longitudinal range of the co-latitudinal impacts is restricted to ≤60°, which is the case here. It is thus highly unlikely that these represent a random array. The two smallest impact structures, Obolon' (15 km) and Red Wing (9 km), have essentially identical trajectories with respect to the latitude-parallel trajectory of the other three. Obolon' and Rochechouart (the easternmost pair) define a great circle that has a declination of 37.5°, while Red Wing and Saint Martin (the westernmost pair) define a great circle that has a declination of 43.4°. Thus, they have the same sense and essentially the same magnitude of rotation with respect to the small-circle trajectory. If the longitudinal offset of 43.5° is removed for Red Wing and Saint Martin, while maintaining their latitudes, a best-fit great circle with a delineation of 37.2° is obtained for the four 'end' craters (Red Wing, Saint Martin, Rochechouart and Obolon') (Fig. 2). Deviations of these data from the best-fit great circle are very small (<0.4°).

From the temporal and spatial constraints, we conclude that Saint Martin, Manicouagan and Rochechouart were generated by projectiles that were essentially coaxial with respect to each other (like Shoemaker–Levy 9; refs 24, 25). The spatial relations between the projectiles that generated Obolon' and Red Wing and those that generated the three larger impacts are not clear. Red Wing, at only 9 km diameter, could have been produced by a fragment of the same projectile that generated the larger Saint Martin structure.

It is probable that there were more than five impact structures generated by the fragmented bolide. Those craters generated by fragments that hit the Tethys or Panthalassa oceans rather than Pangaea, however, would have been subsequently destroyed by subduction. It is of interest to note that two other impact structures show possible spatial associations with the five already discussed. Wells Creek, Tennessee, USA (12 km diameter, 200 ± 100 Myr in age)[3], lies on a great circle that intersects Manicouagan, with a declination identical to that of the two great circles shown in Fig. 2 (37.2°). Newporte, North Dakota, USA (3 km diameter, <500 Myr in age)[3], lies on the same great circle as, and between, Red Wing and Saint Martin. However, the age constraints for these two structures will need refining before any association with the five principal



Crater name	Present Lat.	Present Long.	Reconstructed Lat.	Reconstructed Long.
Rochechouart (R)	45.83	0.93	23.5	16.6
Manicouagan (M)	51.38	-68.70	22.1	-7.0
Saint Martin (SM)	51.78	-98.53	22.7	-26.9
Obolon' (O)	49.50	32.92	38.6	34.9
Red Wing (RW)	47.60	-103.55	19.1	-31.1

Figure 2 Reconstruction of the North American (Laurentian) and Eurasian plate positions in the Northern Hemisphere of Earth 214 Myr ago (Mercator projection), showing the locations of the five impact structures.

structures can be considered further.

If the five impact structures are contemporaneous then they would have been generated by projectiles of common affinity. Attempts at identifying the body type of the impactor at Manicouagan and Saint Martin have been unsuccessful; melt sheet analyses yield low to undetectable iridium values[26]. Initial work on Rochechouart melt rocks implied contamination by a IIA iron meteorite[27], but subsequent analysis of footwall metal veins revealed an elevated Cr content and Ni/Co ratios more compatible with a chondritic source[28]. Small amounts of kamacite and taenite have been reported in the heavy mineral fractions of allogenic breccia from Obolon'[15], but their presence does not decisively distinguish an iron from a chondritic source. No appraisal has yet been made of Red Wing. Melt sheets may be poor indicators of projectile compositions owing to the effects of crustal dilution, and depending on the velocity of impact and subsequent mode of projectile dissemination[29]. It should also be cautioned that the non-volatile components of comets have chemical compositions close to those of primitive carbonaceous chondrites[30]. Furthermore, because comets comprise roughly equal portions of silicates, hydrocarbons and volatile ices, their expected bulk siderophile contents are expected to be less than one-third that of an undifferentiated carbonaceous asteroid. This may make detection of a cometary projectile difficult. More work is needed to identify the projectile for the five impact structures. Until then, it is not possible to determine whether the source was a comet or an asteroid on the basis of impact structure geochemistry alone.

The Norian stage of the Triassic is marked by one or more major mass extinction events. One of these occurred at the Triassic/Jurassic boundary at ~205 Myr (refs 12, 22, 31) and is associated with impact-generated shocked-quartz-bearing shale beds in Italy[32]. This is significantly later than the 214-Myr multiple impact event described here. However, Benton[33] has alluded to an earlier Carnian-Norian mass extinction event at ~220 Myr, which affected tetrapods and plants on land and certain marine groups[34]. Unlike the end-Triassic, the age of the Carnian/Norian boundary is less well constrained and it is possible that a 214-Myr multiple impact could be associated with an extinction event at that time. As the late Triassic period is now known to contain evidence for a multiple impact event, a renewed effort should be made to study Carnian/Norian boundary and Norian sections with the aim of locating and characterizing the impact ejecta layer, as well as refining biostratigraphic-radiometric correlations for that time period.

The calculated probability of a multiple impact occurring on Earth, comparable to that of Shoemaker–Levy 9 colliding with Jupiter, appears to be low[35]. This is because, relative to Earth, Jupiter's huge mass presents a formidable gravitational attraction and disruptive force for asteroids and comets. Pairs of craters formed by near-simultaneous impact of binary asteroids are expected for ~10% of the impact structures on Earth and Venus[36]. However, a terrestrial multiple impact event resulting from the collision of several projectiles would appear to require a special situation, possibly involving the close fly-by, orbital capture and decay, and consequent clustered strike of a fragmented or weakly coherent comet or asteroid[35]. The mechanisms by which such a particular circumstance may arise now need to be further explored. Critical to identifying any additional crater chains on Earth will be the continued precision dating of proven impact structures, followed by their placing on accurate plate reconstructions for the time of impact. □

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Fission-track ages of stone tools and fossils on the east Indonesian island of Flores

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The islands of Wallacea, located between the Southeast Asian (Sunda) and Australian (Sahul) continental areas, offer unique potential for the study of evolution and cultural change. Located east of Java and Bali, which were periodically connected to the Asian mainland, the Wallacean islands could only be reached by