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Paleopositions of the chains of the meteorite craters on the Earth

Paleopozycje łańcuchów kraterów meteorytowych na Ziemi

Key words: crater chains, meteorite collisions, multiple craters, paleomaps, paleopositions of craters

Słowa kluczowe: łańcuchy kraterów, kolizje meteorytowe, kratery wielokrotne, paleomapy, paleopozycje kraterów

INTRODUCTION

Chains of meteorite craters are quite frequent in the Solar System. There are the chain structures on Ganimede, Callisto (Schenk et al. 1996), Mars, and on the Moon (Meszaros 1985). It is estimated that about 10−15% of the Earth's craters with diameter above 20 km and approximately 14% on the Venus have their companion or companions (Cook et al. 2003). The most notable examples on the Earth are the Kara and Ust-Kara Craters in Russia (Koeberl et al. 1988) and Clearwater Lakes Craters in Canada. Moreover, it is suspected that the crater in the Chesapeake Bay has its companion also (Poag 1999).

It is of some interest to compare this statistics with the number of the systems of gravitationally bounded small objects. The observations that have been carried out so far indicate that about 16% of the near-Earth asteroids are double, or even multiple (Margot et al. 2002; Bottke and Melosh 1996) and this should be reflected in the overall statistics of the impact events on the Earth. Unfortunately, the total number of known meteorite craters is certainly only a small fraction of the total number of impactors that hit the Earth in its history. The number of craters listed in the Earth Impact Database (EID 2010) does not exceed 200, and, except its small subset, there is no precise dating. Consequently, the establishment of which craters, if any, do have a common origin is invalidated by our ignorance. Moreover, there are additional obstacles: even if present in the database, the meteorites that build a genuine chain structure can be separated by large distances, ill-dated, and misplaced as a result of the movement of the tectonic plates, and, consequently, hard to find, to say the least.

In this paper we shall analyze the actual position of the known craters at the moment of the collision with the Earth with special emphasis put on their possible common origin. We shall adopt a positive point of view and assume that there were serial impact events in the Earth's past that produced chains of craters, although it is expected that the geological processes destroyed most of them. Although the idea to analyze the paleopositions of the craters is not new, it is fair to say that it has been employed only marginally. Indeed, Chatterjee (1996) and Spray et al. (2000) tried to find correlations between craters making use of the actual localization of Shiva and Chicxulub in the Cretaceous and the Manicouagan, Obolon, Rochechouart, St. Martin and Red Wing in the Triassic, respectively. Here we shall undertake a more ambitious research program and analyze the paleopositions of the known craters in seven periods, starting from Ordovician.

A GENERALIZED DEFINITION OF THE CHAIN STRUCTURES

To find craters, which belong to such a system, we must precisely define the notion of the crater chain itself, select geologically simultaneous events and subsequently place them on the maps which show location of the tectonic plates at the appropriate time in the past. According to the standard definition, a crater chain is a regularly spaced row of three or more impact craters with similar sizes and apparently identical ages (Bottke et al. 1997). Unfortunately, this definition, except the latter condition, is too restrictive for our purposes The generalized definition should allow for rows of craters both nonequispaced, of various diameters, and, in our opinion, there should be no limitations posed on distances. To avoid apparently uninteresting structures composed of the craters of dramatically different sizes, in which the most prominent body is responsible for the main post-impact effect, we shall restrict ourselves to the meteorite collisions leading to comparable results. Inspection of the photographs of the serial bombardment of the Jupiter in 1994 by the Shoemaker-Levy-9 (Zahne et al. 1994) comet clearly shows that the standard definition can be violated. Typically, it is caused by the rotation of the bombarded celestial body and nonequispaced location of the impactors on the orbit. Moreover, one issue requires further clarification: although it is implicitly assumed that the impactors should have the same origin, one may weaken this demand and allow for situations in which the massive bodies of different origin form a chain structure in a sense of the generalized definition.

POTENTIAL CHAIN STRUCTURES AND THEIR PALEOPOSITIONS

Although searching for the chains of craters has been undertaken earlier, their scope has been limited to the adjacently placed forms. It seems that one can single out a potential 700 km-long chain structure in Kansas and Illinois. It consists of eight circular valleys with diameters varying from 3 km to 17 km. On the other hand, the radar analyses carried out in Africa in the neighborhood of the Aourunga crater in Chad, suggests the presence of another chain (Bottke et al. 1997). Since both chains lie entirely in their respective tectonic plates, the discovery has been substantially facilitated. It has been suggested that the Manicouagan, Obolon, Rochechouart, St. Martin and Red Wing craters also form a chain (Spray et al. 2000). Similarly, one can treat the collisions which gave rise to the Chicxulub and Shiva craters as the remnants of the same event (Chatterjee 1996). In our opinion the Red Wig crater should not be considered as a part of the Triassic chain structure since, according to the Earth Impact Database, it has been classified as Jurassic.

Because of the continental drift, searching for chain structures on the Earth must not be carried out on the maps showing the present location of the tectonic plates. To find paleographic positions of the craters of comparable age we used paleomaps (Scotese, 2001) and followed the chronological order of the confirmed craters as presented in the Earth Impact Database, i.e., we accepted the most probable, according to the authors of the database, age of the craters. As the dating in a number of cases is uncertain, the actual location of some of the craters on the paleomaps may be different.

Inspection of the paleomaps (Figs. 1–7) reveals the rows of craters, which can be considered as chain structures in a sense of the weakened definition. It should be emphasized that the definitive resolution of the problem – whether or not a given row of craters forms a genuine chain structure requires precise dating and field investigations. However, even without a detailed examination it is fair to say that most of the linear or quasi-linear structures are probably accidental. Nevertheless, as we shall demonstrate below, a few structures are more compelling than the others. This, of course, does not exclude the possibility of other choices, which, in turn, may be confirmed as genuine chain structures in the future and satisfy our generalized definition.

For the craters that were created in the Paleogene (Fig. 1), Lower Cretaceous (Fig. 3), Triassic-Jurassic boundary (Fig. 4), Triassic (Fig. 5), Carboniferous (Fig. 6) and Ordovician (Fig. 7) one can consider a few possibilities for chain structures (Table 1).

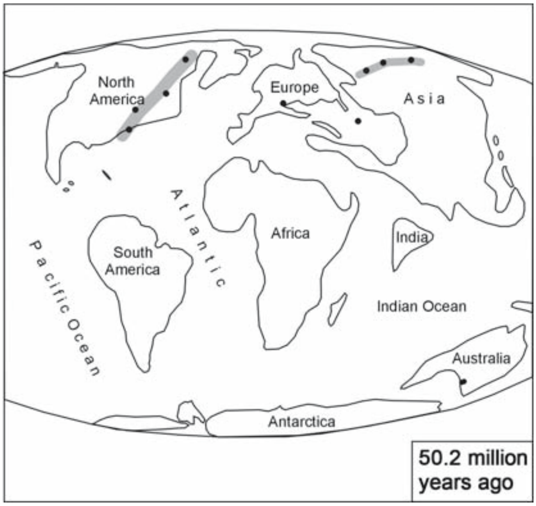

Fig. 1. Meteorite craters (represented as black dots) formed in the Paleogene about 35–45 million years ago. North America top to bottom: Haughton (39), Mistatin (36.4±4), Wanapitei (37.2±1.2) and Chesapeake Bay (35.3±0.1); Europe and Asia left to right: Logoisk (42.3±1.1), Shunak (45±10), Logancha (40±20), Popigai (35.7±0.2) and Beyenchime-Salaatin (40±20); Australia nearly located: Crawford (>35) and Flaxman (>35) (Scotese 2001, EID 2010)

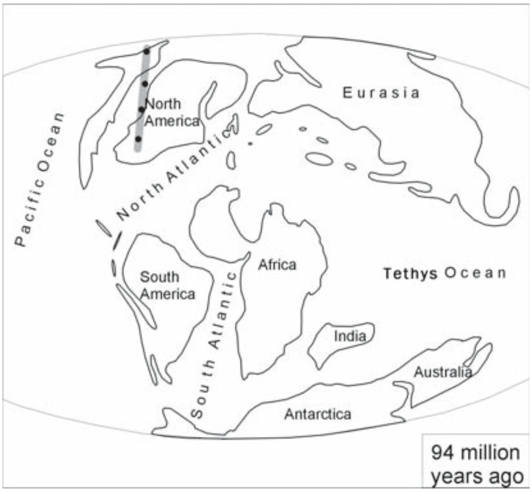

Fig. 2. Meteorite craters (represented as black dots) formed in the Cretaceous about 95 million years ago. Top to bottom: Avac (3–95), Steen River (91±7), Deep Bay (99±4) and Kentland (<97) (Scotese 2001, EID 2010)

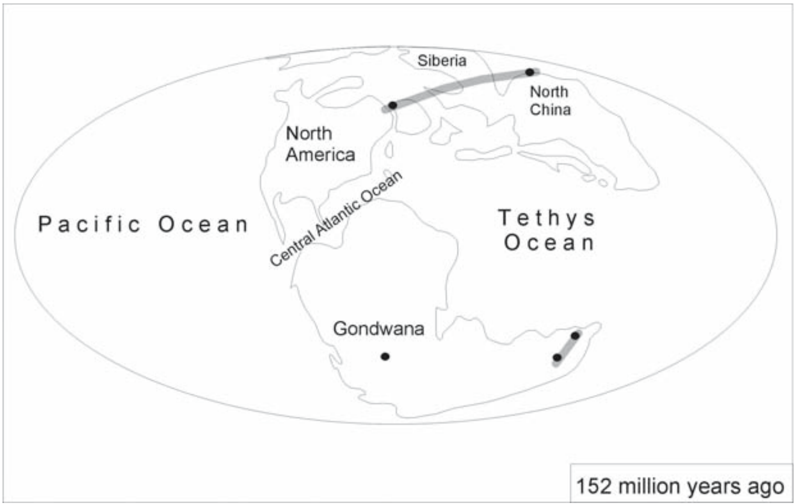

Fig. 3. Meteorite craters (represented as black dots) formed about 140–145 million years ago. Craters Mjølnir (142 ± 2.6) and Tabun-Khara-Obo (142.5 ± 0.8) in Europe and Asia, crater Liverpool (150 ± 20) in Central Gondwana, craters Gosses Bluff (142.5 ± 0.8) and Morokweng (145 ± 0.8) in the east part of Gondwana (Scotese 2001, EID 2010)

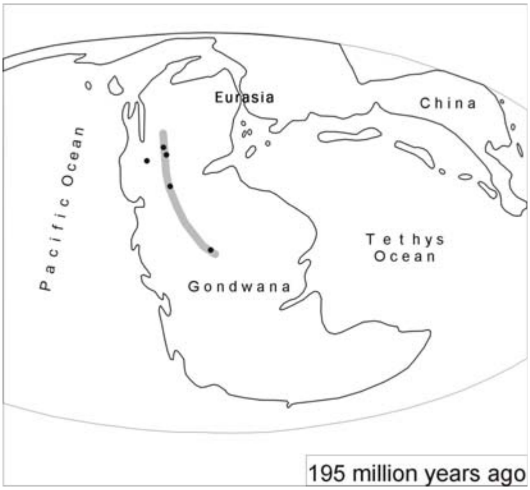

Fig. 4. Meteorite craters (represented as black dots) formed about 200 million years ago on paleomap presented tectonic plates 195 million years ago. From top to bottom: crater Viewfield (190 ± 20), Red Wing (200 ± 25), in the west Cloud Creek Crater (190 ± 30), ill-dated crater Wells Creek (200 ± 100) and in the south Riachao Ring Crater (~200) (Scotese 2001, EID 2010)

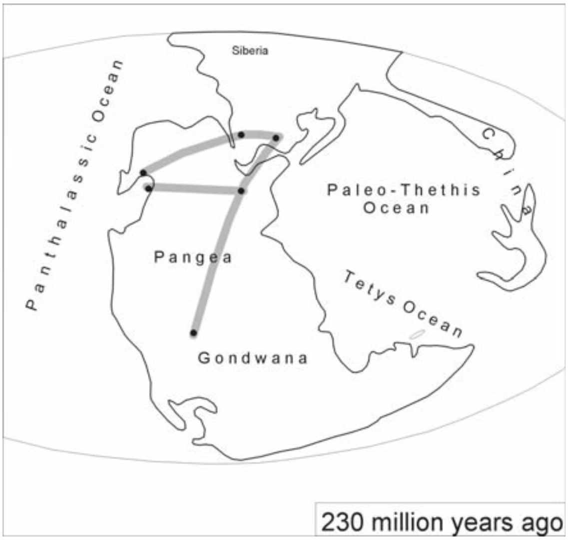

Fig. 5. Meteorite craters (represented as black dots) formed about 220–230 million years ago on paleomap presented tectonic plates in Triassic, 237 million years ago. From left to right: Karikkoselka (~230) and Kursk (250 ± 80), more in the south: Gow Crater (~250), Saint Martin Crater (220 ± 32) and Rochechouart Crater (214 ± 8) and solitary structure in the south: Araguainha Crater (244 ± 3.25) (Scotese 2001, EID 2010)

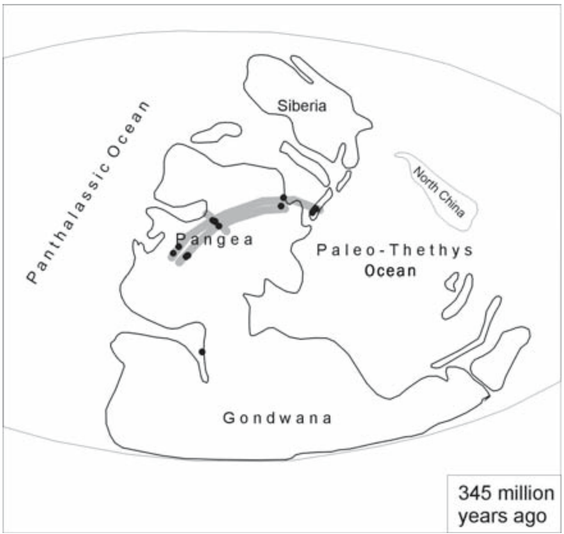

Fig. 6. The meteorite craters (represented as black dots) formed in the Carboniferous about 300 million years ago. Left to right: Crooked Creek (320±80), Decaturville (<300), Middlesboro (<300), Des Plaines (<300), Clearwater Lakes (290±20), Ile Rouleau (<300), Dobele (290±35), Mishna Gora (<300), Ternovka (280±10) and Kursk (250±80). The most southward solitary crater structure: Serra da Cangalha (<300) (Scotese 2001, EID 2010)

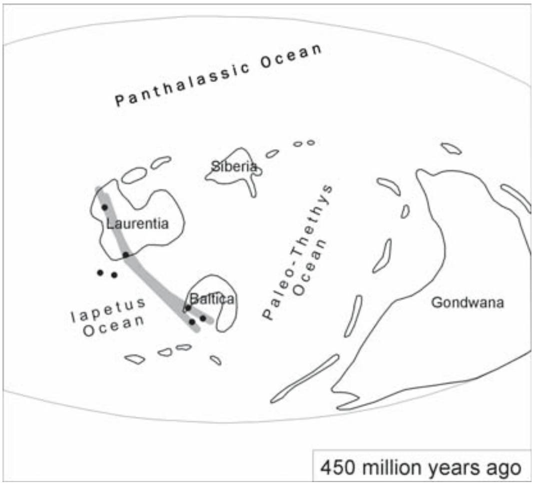

Fig. 7. Meteorite craters (represented as black dots) formed 445–450 million years ago on the Ordovician paleomap. From top to bottom and from left to right: Pilot Crater (445 ± 2), Slatelsland Crater (450), Calvin Crater (450 ± 10), Ames Crater (470 ± 30), Traaveren Crater (~455), Lockne Crater (455) and Kaardla (~455) (Scotese 2001, EID 2010)

Tab. 1. Possible chain structures

Periods	Suggested crater chains
Paleogene (Fig. 1)	1. Haughton, Mistatin, Wanapitei and Chesapeake Crater 2. Logancha, Popigai and Beyenchima Crater
Cretaceous (Fig. 2)	1. Avac, Steen River, Deep Bay and Kentland
Lower Cretaceous (Fig. 3)	Doublet craters: 1. Mjølnir and Tabun-Khara-Obo 2. Gosses Bluff and Morokweng
Triassic-Jurassic (Fig. 4)	1. Viewfield, Red Wing, Wells Creek and Riachao Ring Crater
Triassic (Fig. 5)	1. Gow, Karikkoselka and Kursk 2. Sant Martin and Rochechouart 3. Araguainha, Rochechouart and Kursk
Carboniferous (Fig. 6)	1. Crooked Creek, Ile Rouleau, Mishna Gora, Ternovka and Kursk 2. Decaturville, Crooked Creek, Ile Rouleau and Dobele 3. Ile Roule, Clearwater Lake East and Clear Water Lake West
Ordovician (Fig. 7)	1. Pilot, Slatelsland, Traaveren and Kaardla 2. Pilot, Slatelsland and Lockne

The craters located close to each other, such as Clearwater Lakes or Crawford and Flaxman (which are dated back to the Carboniferous about 290 million years ago and to Paleogene about 35 million years, respectively) are most probably double, but may be parts of some larger structures as well. Both dating and diameters of the biggest

Paleogene craters: Chesapeake (90 km) and Popigai (100 km), suggest that they could have common origin. Resolution if these craters are double or whether they are a part of a greater system (visible in Figure 1) requires further studies.

With the assumption that the dating is exact, the Cretaceous impacts plotted in Figure 2. satisfy the restrictive chain definition as they are approximately equidistant and of comparable diameter (Deep Bay – 13 km, Kentland – 13 km, Avak – 12 km and Steen River – 25 km).

ESTIMATIONS

One expects that the chains that can potentially be found on the Earth are only a fraction of the total amount of such events. It is simply because the majority of the chains or their constituents have been obliterated in the geological and tectonic processes. Indeed, the post-Late Heavy Bombardment (LHB) impact rate related to the extraterrestrial bombardment episodes indicate that the cumulative number of craters, N, with a diameter greater than D given in kilometers satisfies the approximate phenomenological formula $N = \alpha D^{-2}$, where $\alpha \approx 4.57 \times 10^6$ (Glikson 2001). For $D \geq 20$ it is expected that the cumulative number of craters should be at least 11,400. One can compare this result with the actual number of the known craters, which, according to the Earth Impact Database, equals 42. It follows then that the minimal number of multiple craters with $D \geq 20$ km exceeds 1,500, however, the vast majority of them are expected to be double. This estimation is based on the observation that about 16% of the near-Earth asteroids comprise gravitationally bounded many body systems. The thus obtained number of multiple craters is, of course, highly speculative, but we believe that it approximately reflects the actual situation. All this shows that the serial bombardment can be (and probably is) quite frequent in geological sense. Depending on the masses of the impactors, their velocities, mean density and the characteristics of the target rocks it is expected that a few impactors of the medium size can cause similar effects as a big asteroid of the Shiva size.

FINAL REMARKS

We understand that verification whether a given set of craters forms a genuine chain structure is hard as there has been no, in general, comprehensive examination of their origins, age and chemical composition. All we can do is to carry out the quest for a more precise dating of the known structures and search for undiscovered ones making use of the important impact markers such as microtektites, shock quartz or post-impact sandstone. It is expected that these investigations would allow to determine more exactly the percentage of the multiple collisions with the Earth. Having established the existence of the chain craters and having determined the probability of their occurrence, we can hypothesize that such structures are not limited to relatively small and closely-spaced objects.

REFERENCES

Bottke W. F., Melosh H. J., 1996. Binary asteroids and the formation of doublet craters. Icarus 124, 372–391.

Bottke W. F., Richardson D. C., Love S. G., 1997. Making crater chains on the Earth and Moon with planetary tidal forces. Conference Paper, 28th Annual Lunar and Planetary Science Conference, 27, 141–142.

Chapman C. R., 1993. Comet on target for Jupiter. Nature, 363, 492–493.

Chatterjee S., 1996. Multiple Impacts at the KT Boundary and the Death of the Dinosaurs. Proceedings of the 30th International Geological Congress, Beijing, China, 4–14 August 1996, 26, 31–54.

Cook C. M., Melosh H. J., Bottke W. F., 2003. Doublet craters on Venus. Icarus 165, 90–100.

EID, 2010. Earth Impact Database. Planetary and Space Science Centre, University of New Brunswick.

Glikson A. Y., 2001. The astronomical connection of terrestrial evolution: crustal effects of post-3.8 Ga mega-impact clusters and evidence for major 3.2 ± 0.1 Ga bombardment of the Earth-Moon system. Journal of Geodynamics, 32, 205–229.

Koeberl C., Nazarov M. A., Harrison T. M., Sharpton V. L., Murali A. V., Burke K., 1988. The Kara and Ust-Kara impact structures (USSR) and their relevance to the K/T boundary event. Topical Conference on Global Catastrophes in Earth History: An Interdisciplinary Conference on Impacts, Volcanism, and Mass Mortality, 95–96.

Margot J. L., Nolan M. C., Benner L. A., Ostro S. J., Jurgens R. F., Giorgini J. D., Slade M. A., Campbell D. B., 2002. Binary asteroids in the Near-Earth Object population. Science 296, 1445–1448.

Meszaros S. P., 1985. A geographic comparison of selected large-scale planetary surface features. In NASA, editor, Scientific and Technical Information Branch, NASA Technical Memorandum 86147.

Poag C. W., 1999. Secondary craters from the Chesapeake Bay impact. In: 30th Annual Lunar and Planetary Science Conference.

Schenk P., Asphaug E., McKinnon W. B., Melosh H. J., 1996. Historical examples of tidally split comets: crater chains on Callisto and Ganimede. Icarus 121, 249–274.

Scotese C. R., 2001. Atlas of earth history, Paleomap Project. Paleogeography, Arligton, Texas 1, 52.

Spray J. G., Kelley S. P., 2000. Terrestrial multiple impact events. In: Catastrophic Events and Mass Extinctions: Impacts and Beyond, 216–217, Boulder, USA.

Zahne K., Mac Low M-M., 1994. The collision of Jupiter and Comet Shoemaker-Levy 9. Icarus 108, 1–17.

STRESZCZENIE

W Układzie Słonecznym powszechne są łańcuchowe struktury kraterów meteorytowych. Spotyka się je zarówno na planetach (Mars, Merkury), jak i na księżycach (Ganimedes, Kalisto, Księżyc).

Podobne formy znajdują się także na powierzchni Ziemi. Szacuje się, że około 15% bolidów tworzy układy wielokrotne.

Definicja łańcuchów kraterów meteorytowych przedstawiona przez Bottkego i in. (1996) mówi o formach o zbliżonej średnicy, identycznym wieku i pochodzeniu, ułożonych liniowo w takich samych odległościach od siebie. Definicja ta jest zbyt restrykcyjna, gdyż automatycznie wyklucza nawet najbardziej znaną kolizję łańcuchową komety Shoemaker-Levy-9 z Jowiszem. Dlatego też proponujemy ogólniejszą definicję, zgodnie z którą kratery tworzące łańcuch nie muszą znajdować się w jednakowych odległościach ani nie muszą mieć podobnych rozmiarów. Mogą się znajdować w różnych, często bardzo znaczących odległościach, ich rozmiary mogą być urozmaicone, a cała struktura może mieć charakter quasi-linearny. Jedynym kryterium, które musi być spełnione w przypadku ogniw łańcucha, jest ich równowiekowość. Oznacza to, że w skrajnych i ekstremalnie rzadkich przypadkach łańcuch może być utworzony przez niepowiązane ze sobą asteroidy lub komety.

Poszukiwania łańcuchów kraterów meteorytowych na Ziemi jest utrudnione ze względu na procesy erozji i denudacji, procesy górotwórcze, a także ze względu na dryf płyt litosfery, który powoduje rozerwanie pierwotnie linearnych struktur i przemieszczenie ich często na znaczne odległości, a także obrót płyt, co dodatkowo utrudnia poszukiwania.

Aby odszukać potencjalne łańcuchy, konieczne jest przedstawienie położenia kraterów w chwili ich powstania. W celu przedstawienia pierwotnej lokalizacji kraterów meteorytowych z danego okresu zostało wykorzystanych siedem paleomap (Scotese 2001), map prezentujących rozkład płyt litosfery w danym momencie w przeszłości dla siedmiu okresów (ordowiku, karbonu, triasu, przełomu triasu i jury, kredy dolnej, kredy górnej i paleogenu). Naniesione na nie kratery (EID 2010) o zbliżonym wieku pozwalają na przybliżoną lokalizację potencjalnych łańcuchów. Sprawdzenie, czy struktury te faktycznie powstały w jednym czasie, wymaga dokładniejszych datowań kraterów, jednakże obraz ten pozwala na wytypowanie form, które mogą być brane pod uwagę w dalszych badaniach.