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FROM THE CONCEPT OF SALIENT AND REENTRANT ANGLES BY LOUIS BOURGUET TO NICOLAS DESMAREST'S DESCRIPTION OF MEANDERING RIVERS

BY

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ABSTRACT

Between 1729 and 1803, the abstract concept of corresponding salient and reentrant angles evolved into the modern description of meandering rivers. Louis Bourguet believed that the concept of corresponding angles in mountains was the key to the theory of the earth. While his observations were, in fact, based on entrenched meanders, he nevertheless saw only a symmetry in mountains as the proof, revealed to him by Providence, that these mountains had been formed by movements of terrestrial rotation during the time of the Deluge and not by present-day agents over a long period of time. In 1749, Buffon drastically changed Bourguet's original concept and said that ocean currents had formed mountains and valleys on the sea floor and that ancient ocean currents displayed corresponding angles as present-day meanders do. This interpretation was refuted by most French speaking Eighteenth-Century naturalists. While Pallas, Saussure, and Laméthérie objected merely to the concept of ancient ocean currents, Boulanger, De Luc, and Desmarest compared the alleged ancient ocean currents with present-day meandering rivers. Boulanger described the morphology of the Marne valley and De Luc proposed the law that rivers tend to meander because they follow a course of least resistance. This point is still being debated today. In 1803, Desmarest came to the conclusion that the concept of corresponding angles had been merely used by naturalists to prove or disprove a theory and that nobody had actually studied meandering rivers which in fact produce such corresponding angles. His description of the latter is very close to modern ones. He even proposed the term of "inclined planes" for salient angles, and of "cliffs" for reentrant angles.

RÉSUMÉ

Entre les années 1729 et 1803, l'idée abstraite d'angles saillants et d'angles rentrants a évolué en une description moderne de méandres. Louis Bourguet a considéré l'observation d'angles saillants et rentrants dans les montagnes comme la clef principale de la théorie de la terre. Cette observation était en fait basée sur les méandres encaissés mais Bourguet ne voyait qu'une symétrie admirable et une preuve révélée par la Providence que ces montagnes étaient formées par divers mouvements de la rotation de la terre pendant le déluge et non pas par des causes actuelles pendant une longue durée. En 1749, Buffon a adopté l'idée d'angles saillants et rentrants en disant que les courants marins ont formé les montagnes et les vallées avec leurs angles correspondants au sein de la mer pendant de longs siècles. Il a ainsi apporté un changement radical à la première idée de Bourguet en expliquant que les anciens courants de la mer autant que les rivières actuelles

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présentent des angles alternativement opposés. Cette interprétation a été rejetée par la plupart des naturalistes de langue française du XVIII[e] siècle. Pallas, De Saussure et De Lamétherie n'ont que critiqué l'idée des anciens courants marins tandis que Boulanger, De Luc et Desmarest ont comparé les prétendus anciens courants marins avec les méandres actuels. Boulanger a décrit la morphologie de la vallée de la Marne et De Luc a proposé la loi qu'une rivière commence à serpenter parce qu'elle suit la loi du moindre effort. Aujourd'hui on reste toujours indécis sur ce point. En 1803, Desmarest a conclu que l'idée d'angles saillants et rentrants a été uniquement utilisée par beaucoup de naturalistes pour prouver ou rejeter une théorie et que personne n'avait en fait étudié les méandres qui eux ont produit ces angles correspondants. Sa description est très voisine des idées modernes. Il a même proposé le nom de «plans inclinés» pour les angles saillants et de «bords escarpés» pour les angles rentrants.

INTRODUCTION

When Louis Bourguet first proposed the concept of corresponding salient and reentrant angles, he tried to prove that all big mountain chains, valleys, and seas received their present shape during the time of the Deluge and hence not by various present-day agents over a long period of time. Buffon used Bourguet's concept to prove that, on the contrary, mountains and valleys had been shaped by ocean currents on the bottom of the sea over a long period of time. As such, the concept was criticized by Nicolas-Antoine Boulanger, Peter Simon Pallas, Jean-André De Luc, Horace-Bénédict de Saussure, Jean-Claude de Lamétherie, and finally rejected by Nicolas Desmarest.

To my knowledge, only two historians have pondered upon this strange concept. Kenneth L. Taylor believes that "Bourguet aroused the curiosity of some later observers because in the middle of a cosmogony in the *ad hoc* tradition, he seemed to be trying to inject the seed of a natural law" and that French speaking naturalists were more interested in his empirical observations, namely the principle of corresponding angles, than in his cosmogony (1974, p. 8). Taylor states that without Buffon, Bourguet would probably never have achieved much fame and that most later naturalists failed to make any distinction between the concepts by Bourguet and Buffon and merely commented on Buffon's interpretation (1974, p. 5). François Ellenberger (1978, p. 52-59, and personal communication, 1985) has tried to understand the reasons why Bourguet formulated his concept of corresponding angles. Ellenberger mentions that after having crossed the Alps many times, Bourguet was having religious doubts when he observed irregular patterns in the exterior shapes of mountains. Thus he proposed the concept of corresponding angles because of his belief in final causes while Buffon, after him, saw in corresponding angles proofs of present-day causes, that is ocean currents.

This paper gives a close analysis of Bourguet's concept and of his cosmogony in his *Mémoire sur la théorie de la terre,* attached to *Lettres philosophiques sur la formation des sels et des crystaux...* (1729), his *Cours de Philosophie* (1734), and his *Traité des pétrifications* (1742) in order to find out how he explained the formation of corresponding angles. It shows that Bourguet was, in fact, describing entrenched meanders but that he did not see the characteristics of these rivers but had eyes only for the regular

symmetry of mountain shapes. His contemporaries, thereafter, gave this abstract concept a more and more realistic turn and transformed an apparent symmetry in mountains into the realistic description of meandering rivers. The reaction of each naturalist highly depended upon his own theory of mountain-building or absence of theory.

BOURGUET'S MÉMOIRE SUR LA THÉORIE DE LA TERRE

In 1729, Bourguet claimed that nobody before him had noticed the surprising regularity of the structure of great mountain chains although their west-east and north-south direction had been observed for quite some time (I am using throughout this text the word "structure" as it was understood by Eighteenth-Century naturalists, namely the exterior shape of mountains. The modern geological term "structure" refers to the position of beds resulting from mountain-building processes as dimly perceived by Saussure). Bourguet stated that after having crossed the Alps thirty times in fourteen different places and the Apennines twice, and after having made many trips to all these places, including the Jura Mountains, he discovered the fundamental "truth" that the contours of all mountains are very much like fortifications (p. 181).

These are his words to explain the concept of salient and reentrant angles:

> When the body of a mountain lies in a west-east direction, it forms advances which point as much as possible toward the north or the south. In other words, when the length of the mountain is parallel to the equator, its angles are parallel to the meridian, and when the length of the mountain is parallel to the meridian, its angles are parallel to the equator. This wonderful regularity is so noticeable in narrow valleys ["vallons"] that one has the feeling of walking in a "chemin couvert" [that part of a wall or ramp surrounding the moat of a fortress which lies between the parapet and the moat]. For instance, if one travels from north to south in a narrow valley, one notices that the mountain on your right forms advances or angles which point toward the east while those of the mountain on your left point toward the west so that salient angles correspond to reentrant angles which are always in a reciprocal position one to the other. If on the contrary the valley stretches west-east, the angles of the left-side mountain point toward the south while the angles of the right-side mountain point toward the north. In large valleys, such angles formed by mountains are less acute because the slope is less steep and the angles are at a greater distance from each other. In plains, angles are visible only in riverbeds which ordinarily occupy the middle of the valley. The natural riverbends correspond to the most marked advances or to the most advanced angles of the mountains which abut against the land where rivers flow. This structure which is common to ocean floors, lakes, rivers, and valleys is so true that the author dares to point it out to the eyes of all men (p. 181-182).

In his description of phenomena at the surface of the earth, he repeated the concept in a more intelligible fashion:

> When two mountains lie side by side, they form valleys of various widths and the advances of these mountains correspond alternatively to each other, namely the salient angle corresponds to the reentrant angle and so forth.
> These advances are more frequent in "vallons" where the angles are more acute, they are less frequent and more obtuse in larger valleys. In plains, these advances are visible only in the bed of rivers which flow normally in the middle of the valley where they form their natural bends. In the ocean these advances can be noticed merely in cliffs along the seashore (p. 195-196).

There is no doubt that Bourguet was highly impressed by the salient and reentrant walls of entrenched meanders—whether these rivers were flowing east-west or north-south, they always meander almost at right angle—hence his term of "fortification" and "chemin couvert". He found these angles less visible in larger valleys and plains, and along the seashore; he probably described rocky promontories, which are being eroded by the sea, as the salient advances and the adjacent beaches, where sediments from the eroded cliffs are deposited, as the reentrant angles.

His eyes being only fastened on these "fortifications", he seemed to have no understanding for the processes of meandering rivers in floodplains. He did not link the bends along meandering rivers, which he described in a chapter on the destruction of the earth, with his observation of corresponding angles in entrenched meanders. In that chapter he said:

> Torrents, rivers, and streams carry great quantities of earths, sand, and gravel, not only from mountain tops, but also from layers in the riverbanks. This material raises the bed of the river, forms bends and islands along the river (while the velocity causes the waters to erode this material elsewhere) and dammages valley floors. Lighter material is carried to the sea to form sandbars and deltas at the mouth of the river (p. 209).

Bourguet mentioned here erosion, deposition, and meanders in rivers which eventually flow into the sea, but he saw no salient and reentrant angles as if he had never observed meanders in floodplains. There are actually only entrenched meanders in the Jura Mountains and in Alpine passes where he travelled from Italy to Switzerland.

Bourguet stressed that the concept of corresponding angles is the key to the theory of the earth and that it is capable of invalidating all previous hypotheses. He believed that naturalists have failed to look at the true structure of mountains and their reciprocal relationship. To this concept he added the fact that fossil shells found in layers in mountains are always filled by the same material in which they are enclosed.

He stated that if naturalists had considered these phenomena, they would not have proposed "such ideas as particular inundations, storms, or terrible earthquakes, nor 'des Repanduës ou Alluvions' [alluvial deposits] which lasted between ten and thirty thousand years, nor comets or 'pericycloses' or perpetual circulations etc. because their great insight would have shown them that these nice inventions do not correspond in any way to the phenomena mentioned above..." (p. 182-184).

In this passage, Bourguet criticized naturalists who had proposed causes which are still active today such as inundations, storms, earthquakes. The terms "repanduës" and "pericycloses" were used by Henri Gautier and Father Castel respectively. Ellenberger has clearly shown that Bourguet was in particular referring to the "repanduës" or "alluvions" postulated by Henri Gautier in *Nouvelles conjectures sur le globe de la terre,* published in 1721 (Ellenberger, 1977, No. 7, p. 15; No. 9-10, p. 21, 47, 52, 132). Gautier's system appeared particularly irksom to Bourguet because it was unorthodox and necessitated, furthermore, thousands and thousands of years to erode mountains and to deposit material in the sea from where after another long period of time new mountains would emerge. Therefore, Bourguet reacted strongly in his theory of the earth in 1729 and in his later work (1742, p. 1-52) to prove that mountain-building had lasted merely the time of the Deluge. The concept of "pericycloses" was apparently proposed by R. P. Castel to whom Bourguet referred (1729, p. 179). In the *Mémoires de Trevoux,* Castel gave the following vague theory about the presence of fossil plants in France: ... "the third manner is, I must admit, the least probable because it has been the least proven, or the one to which one has paid the least attention. It concerns a regular circulation of all terrestrial bodies, both solid and liquid, which carries earths and gravels as well as water either from the lands to the seas or from the seas to the lands passing through the center of the earth..." Father Castel believed that stones found at Saint-Chaumont may have arrived there by some secret subterranean passages with imprints from America, from Asia, or from anywhere else (1722, reprint 1968, p. 277-278).

A close analysis of Bourguet's propositions for a theory of the earth is necessary to understand why he considered corresponding angles so important for his theory of the earth:

1. Our earth has taken its present form at the same time with the exception of some minor changes caused by earthquakes and storms.
2. The form and the present structure of the earth show that it was once in a state of fluidity.
3. The present state of the earth is very different from the one it received in the origin and kept for several centuries.
4. The solid matter of the earth was at the beginning less dense than after the earth changed.

5. The original hardness of the earth diminished slowly together with the speed of the earth so that after a certain number of revolutions on its axis and around the sun, the earth dissolved and its previous state changed and its structure was destroyed.

6. To acquire its present form, the earth needed at least the time of a revolution around the sun.

7. There can be no sound explanation of the shape of the earth without admitting its movement around its axis and around the sun.

8. The earth lost ist former shape at the time of the Spring equinox and started to take on a new shape during the Fall equinox.

9. While all its solid parts were dissolved in water, shells and other remains of the plant and animal kingdom were introduced into these dissolved materials and the waters stayed on top according to their specific gravity.

10. The material of mountains and of subterraneous and submarine vaults hardened first whereas the material of valleys and plains hardened last. But neither was immediately as dense as it was to become later.

11. There is such a relation between all the mountains that they could not have been formed independently from each other.

12. The summit of mountains acquired at first the shape of ocean waves from the poles to the equator and from the equator to the poles. They remained, however, in an east-west direction depending upon their more or less active resistance to the movement of the earth from west to east.

13. The mountains acquired their present position in relation to each other in accordance with the volume of their mass, their density, and solidity received at the time when concentric layers were uplifted, caused by an acceleration of the movement of the earth, during the time of the Fall equinox.

14. The disposition of layers and rocks depended also upon the various degrees of hardening and solidity received at the beginning, upon their relation to the movement of the earth, and upon the uplifting and the general and particular direction of mountains of which they are part.

15. It is precisely the revolution of the earth, its relation to the moon, the movement and the weight of waters, the direction of winds, and a combination of the movement of all these agents impressed upon parts of the earth which had recently received a degree of hardening that caused mountains to be lifted, valleys and plains to be lowered, and subterraneous and submarine vaults, as well as the basins of rivers, ponds, lakes, and seas to be formed.

16. A successive dissolution of the material of the ancient world and a gradual lifting of the layers of the new world are the true cause of the various layers where the laws of gravity are not always observed.
17. The state of the ancient world before its change was not preceded by any other previous state because all the material originating from the ancient world seems to have been produced by a tumultuous crystallisation and a sudden precipitation of an infinite amount of molecules with particular shapes which became mixed during these two operations which were caused by a sudden movement during their formation.
18. All the remains of terrestrial and marine plants found in the layers of the earth prove that the ancient world was as inhabited as the new one (p. 211-215).

The remaining eight sections shall be omitted because they merely treat the future of the earth and its end by fire.

From the above it is evident that Bourguet had no clear explanation for the formation of corresponding angles. A slowly consolidating semi-liquid mass allegedly responded to the earth's movement around its axis and around the sun and produced ripples like ocean waves running from north to south and intersecting east-west ripples aligned along the equator (section 12). No explanation is given why the intervals between mountains displayed corresponding angles. Bourguet mentioned that mountains and subterraneous and submarine cavities hardened first while valleys and plains did so last (section 10) which seems to imply that the waters had abandoned mountains and the interior of the earth while the valleys were still being eroded. Elsewhere he said that mountains were lifted while valleys were lowered (section 15) which contradicts the idea of valley erosion and seems to suggest that valleys formed fissures between mountains. But again, Bourguet did not specify that these fissures were running in a zigzag fashion. [The symmetry of mountain chains had been mentioned by Father Feuillée as indicated by Bourguet (1729, p. 184) and Athanasius Kircher (1664-1666, Tome I, Book II, Chapt. II, p. 56) also described mountain chains surrounding the earth so as to hold it together.]

BOURGUET'S COURS DE PHILOSOPHIE

In his philosophy course at Neuchâtel, Bourguet specified that the structure of mountains dictates the direction of valleys, lakes, and seas and that salient and reentrant angles cause rivers to meander:

> ... These angles are always in a reciprocal position so that if one walks in a valley, one observes that they are alternatively salient and reentrant... These angles shape

> the contours of rivers and force them to meander. They are less pronounced in large valleys, and their sides are even more extended in plains. In the ocean, these angles are visible only in the most advanced promontories.
>
> This wonderful disposition of the solid earth has escaped all ancient and modern philosophers, even those which made it their task to write a theory of the earth. It was revealed to us by Providence during the frequent travels that took us in the past through the Alps, the Apennines, and the Jura Mountains. Those of our auditors who might have any doubts are asked to examine the Val de Travers and the bed of the Seyon, in particular from the bridge of the Seyon Mill, till Valangin and in the Val de Ruz. We must, however, know how to observe these sites because the angles are noticed only when trained to observe and follow the shapes of their sides (1734, p. 434-437).

This manuscript contains three new points: 1) The structure of mountains dictates meandering rivers. 2) Corresponding angles were revealed to Bourguet by Providence. 3) Some corresponding angles can been witnessed in the Jura Mountains at specific places. He advised, however, some caution to his local audience in regard to the presence or visibility of corresponding angles: only the trained eye can see them.

A look at the map (Carte nationale de la Suisse, sheets 1144, 1163, 1164) shows that in the Val de Travers, entrenched meanders of the Areuse follow a west-east sloping synclinal valley whereas the Seyon cuts right through the ridges of anticlinal mountains between Valangin and Neuchâtel forming the gorges of the Seyon with corresponding angles best displayed in entrenched meanders. To the north of Valangin, the same river displays entrenched meanders in a large synclinal valley. It is evident that Bourguet's examples of corresponding angles do not show any particular symmetry of tectonically controlled mountains or valleys. Some rivers flow in synclinal valleys, others cut through anticlinal mountain ridges, directed by an older surface to form superposed rivers. Still others follow wrench faults or cut across the lower part of anticlinal axes. As many naturalists in his century, Bourguet probably tried to explain with a few general laws how mountains and valleys were formed. Tischer (1981-1982) has mentioned that many naturalists were still under the influence of the success story of general laws such as Galileo, Kepler, and Newton had found. Eighteenth-Century naturalists felt that since their predecessors had made such drastic scientific advances with the discovery of one—in the case of Kepler, three—principles or laws, why was it not possible to do likewise in earth sciences? (Tischer, 1981-1982, p. 51-52). Bourguet thus considered the concept of corresponding angles the key to the theory of the earth and it is no surprise that Buffon accepted it as such because he also believed that a few general laws could explain mountain-building.

BOURGUET'S TRAITÉ DES PÉTRIFICATIONS — CONCLUSION

The year of his death, Bourguet resorted once more to his unfinished theory of the earth saying in regard to mountain-building:

> The relationship between mountains, the symmetry of their contours, the admirable double line formed by their masses which cross at right angles between the tropics—one being parallel to the equator, the other to the meridian—these phenomena I ascribe to the west-east rotation of the earth around the sun, to a reciprocal agitation from south to north and from north to south, to the inclination of 23½° of the earth on both sides of the equator. All these features prove that mountains were formed at the same time but in a successive fashion which lasted as long as it took the earth to rotate around the sun (1742, p. 46).

Bourguet's main point here is again the short time of mountain-building proven by the symmetry of mountain shapes.

In conclusion, Bourguet was not so much interested in the physical explanation of corresponding angles as he was in the refutation of systems which claimed that mountains were formed over a long period of time by present-day causes. In order to refute Gautier and others he needed some general ideas such as the apparent symmetry in corresponding angles produced by various movements of terrestrial rotation whereas the features of present-day rivers seemed too insignificant and unable to point toward great changes in the past. It is possible that Bourguet had religious doubts after having seen the many irregular patterns in mountains, as suggested by Ellenberger (1978, p. 52-59). Bourguet was, therefore, all the more eager to prove a harmonious symmetry in mountains as revealed to him by Providence. He became famous through Buffon because his concept of final causes was changed into a theory of present-day causes: ocean currents and meandering rivers.

BUFFON'S INTERPRETATION OF THE CONCEPT OF CORRESPONDING ANGLES

In his theory of the earth (1749), Buffon took full advantage of Bourguet's seminal ideas, namely the observation of corresponding angles visible along rivers, lakes, and even seas, as well as the notion that mountain chains have shapes of ocean waves. The latter idea was illustrated in spectacular plates by Luigi Ferdinando Marsigli which show a great similarity between wave-like mountains on the ocean floor and those at the surface of the earth (1725, p. 14). Buffon was certainly also influenced by Benoît de Maillet's description of ocean currents which formed accumulations of

sediments on the ocean floor and eventually built the mountains found at the surface of the earth (1755, vol. I, p. 22-83).

Buffon's theory is written in a way that each statement seems to be supported by facts given in nineteen articles of "Preuves" (proofs) or by the opinion of some naturalist. Thus Bourguet's concept was first mentioned at the beginning of Buffon's theory to support the statement that mountains, although of chaotic appearance, are nevertheless strongly related to each other and that salient angles of one mountain always correspond to reentrant angles of the opposite mountain (Buffon, 1749, p. 73, all references will be to this edition).

In his description of the sea floor, Buffon mentioned mountains, valleys, ocean currents, and abundant marine fauna and flora; petrifications of marine organisms in mountains and plains prove, therefore, that these lands were once forming the sea floor where sediments were deposited in layers over a long period of time. He explained the possibility of the formation of mountains by the movement and the sediments in the waters of the ocean saying:

> ... Tides, winds, and all other causes which cause turbulence in the sea must produce by the movement of the waters uneven surfaces and hills on the bottom of the sea, composed of horizontal or similarly inclined beds. With time, these accumulations will increase and form small mountains which shall be aligned in the same direction as the waves of the sea which have formed them. These accumulations will eventually form mountain chains. These chains are prone to hinder a uniform movement of waters and particular movements will ensue. Between two adjacent heights, a current will follow the general direction of mountains and flow as rivers on the earth do by forming a channel with angles which are alternatively opposed to each other during the river's entire course (p. 87-88).

At this point, Buffon gave no explanation on the formation of these corresponding angles, nor did he refer to the "Preuves".

In article V of "Preuves", Buffon gave credit to Bourguet for having well-assembled observations and facts and proposed this "beautiful and great observation which is one of the keys to the theory of the earth, namely the correspondence of angles in mountains", but he regretted the fact that Bourguet "had more knowledge and erudition than sound and general ideas" (p. 193-194). In article IX of "Preuves", Buffon cited almost word for word Bourguet's original concept (p. 321-322). A comparison between the two texts shows that with a few abbreviations, and with the addition that north-south mountain chains were discovered in the new world, Buffon has faithfully copied Bourguet's ideas. It is therefore not his fault if later naturalists failed to make a distinction between his and Bourguet's ideas.

According to Buffon, Bourguet had not used this "key to the theory of the earth" in an appropriate way. His own theory, on the contrary, is based on four principal facts

which cannot be doubted since there are proofs to establish them, namely the fact that the earth, composed of parallel beds everywhere, was once in a state of fluidity; that the seas have covered the lands; that tides and other movements of the waters have produced irregularities on the sea floor; and that ocean currents have given to mountains their contours and their corresponding angles (p. 324). Buffon thus transformed Bourguet's concept into the idea that ocean currents formed our present mountains and valleys based on the fact that they both display corresponding angles. He did not say that present-day rivers follow ancient valleys made by ocean currents but the implication is there and Boulanger, De Luc, and Desmarest were going to criticize it.

In article XIII of the "Preuves" Buffon tried to explain the origin of corresponding angles in ocean currents:

> We shall give an obvious reason for the strange fact mentioned earlier, namely the correspondence of angles in mountains and hills which occur everywhere and can be observed in all countries of the world. Rivers and all running waters form alternating opposed angles in their riverbanks so that when a river bends, one bank forms a reentrant angle into the land while the other bank juts out from the land. Such alternating oppositions of corresponding angles are found along the river's entire course. They are based upon the laws of running water and the action of fluids. While it would be easy to demonstrate the cause of this effect here, it suffices to say that these laws are generally and universally recognized since everybody can see with his own eyes that whenever a riverbank retreats into the land, supposedly at my left hand, the other bank on my right hand juts out from the land. Therefore, ocean currents which must be considered rivers or running waters follow the same rules... (p. 451-452).

Did Buffon know of any rules which regulate the course of meanders as he suggested here? He referred to Edmé Mariotte's *Traité du mouvement des eaux...* in regard to winds blowing over the Mediterranean Sea (Buffon, p. 456), to Bernard Varen's *Geographia generalis* in regard to the velocity of rivers (Buffon, p. 357), and a work by Benedetto Castelli on the flooding of rivers (Buffon, p. 351). None of the authors refer to meandering rivers (Mariotte, 1686; Varen, 1650; Castelli, 1628, 1660). The *Encyclopédie* of Paris did not mention the cause of meandering rivers in the article "Fluides" where D'Alembert wrote an abstract on what was known about the laws of fluids (1757, vol. VII). In the article "Fleuve", D'Alembert pointed to Domenico Guglielmini's important contribution for the understanding of rivers in general in *Della natura de' fiumi,* published in 1739 (*Encyclopédie,* 1757, vol. VII). D'Alembert's articles are, however, too late for Buffon's theory of the earth written in 1749. Moreover, Pierre-Louis-Georges Du Buat wrote in 1786 that "after so many centuries, we are still in almost absolute ignorance of the true laws to which the motion of water is subjected (vol. I, p. vij). It is therefore safe to say that Buffon did not know of any law which explains why rivers meander.

Analysis of Buffon's theory of ocean currents also brings to mind the question of how much was actually known about the sea floor in 1749. When Buffon mentioned the hilly topography of the sea floor, he referred to a map by Philippe Buache on the depths of the ocean between Africa and America (Buffon, p. 71). Fontenelle, Secretary of the Academy of Sciences at Paris, reported a map drawn in 1737 by Buache according to which the mountains of Sierra Leone and the Cordilleras were connected by submarine mountain chains, the island of Fernando de Noronha being one of the summits of these submarine mountains. The theory, supported by "basses" and "vigies" (shoals and "reefs") encountered between Africa and America and based, furthermore, upon a "multitude of soundings and observations made by Mr. Buache", was hailed by Fontenelle to open new horizons for submarine geography (Fontenelle, 1745, p. 76, and 1752, p. 117-124). In a memoir to the Academy, Buache published a map of the British Channel with an "avertissement" saying: "In 1737, the author presented to the Academy of Sciences this map of the Channel, in manuscript form, as well as a map of the ocean toward the equator to show how continents will be connected in the near or distant future" (1752, p. 399-416). In this memoir Buache emphasized that oceans were divided into many basins by submarine mountain chains which hold the earth together (1752, p. 405). [I have not seen this map. It is possible that Lamétherie published a copy of it (1795, vol. II, Plate III).] Buffon also repeatedly cited Varen who gave, however, few details on ocean floors. In Marsigli's work, Buffon might have found local observations on ocean currents, tides, and sediments on the ocean floor in a small portion of the Mediterranean Sea, mostly off Cassis. The data on tides and ocean currents did, therefore, not correspond to worldwide observations by travelers. In short, I believe that there was not enough knowledge on the sea floor to serve as basis for Buffon's assumptions on the formation of mountains and valleys on the sea floor although he repeated the concept for secondary mountains in his *Époques de la nature* in 1778 (*Œuvres complètes,* 1850-1860, p. 455).

In conclusion, Buffon's interpretation of Bourguet's concept of corresponding angles was as unrelated to facts as Bourguet's. However, his theory of the formation of mountains and valleys by ocean currents could be easily visualized so that Boulanger, De Luc, Saussure, Lamétherie, and Desmarest all mentioned that Bourguet's concept included the action of ocean currents. I believe that this negligence cannot be attributed to their confusion between Bourguet's and Buffon's ideas; they simply understood better Buffon's clear and repeated statements on ocean currents than Bourguet's obscure cosmogony. With a few exceptions (Daubenton, 1751, in *Encyclopédie* of Paris, article "Angles correspondants des montagnes", vol. I; Valmont de Bomare, 1775, in *Encyclopédie* of Yverdon, article "Théorie de la terre", vol. 40), most French speaking naturalists found Buffon's interpretation unacceptable, but each one had a different reason.

NICOLAS-ANTOINE BOULANGER'S ANSWER TO THE CONCEPT OF CORRESPONDING ANGLES

The article "Déluge" in the *Encyclopédie* of Paris (1754, vol. IV) was apparently written by Boulanger as mentioned at the end of the text. According to a biography, probably by Diderot, Boulanger, a genius and excellent observer, died very young after having worked for the Department of "Ponts et Chaussées" and spent much time observing natural phenomena in the Marne valley and in Touraine (Boulanger, 1766, Preface).

In this article, Boulanger asked whether the Deluge was universal or partial, where the waters came from, and what the effects of the Deluge were. He believed in the universality of the Deluge, not necessarily based on the Bible, but on ancient traditions kept by nations in the four parts of the world. According to traditions from Istanbul, corresponding angles in straits, mountains, and rivers are proofs of a universal Deluge. Some naturalists claimed, he said, that these angles were not shaped by the waters of the Deluge but are the result of a long stay of the ocean on our lands (p. 797). As another proof of the universal Deluge, naturalists mentioned marine fossils found in mountains and in plains. Without referring to Bourguet or Buffon, Boulanger argued that valleys could not have been carved while marine fossils were deposited:

> If the waters of the Deluge while descending from the summits and the centers of mountains toward the sea were carving, in meandering rivers, all the deep valleys, if these waters have produced the steep slopes in valleys, in mountains, and on sea shores, if these waters have eroded the solid earth in all the places where some resistant or solidly implanted matter forced them to change direction, then these same waters could not have carried marine fossils because these fossils occur only in what is left from all the ancient eroded earth (p. 798).

Since the article "Déluge" does not give any further details on meandering rivers nor his theory of erosion by torrents, we must refer to excerpts given by John Hampton (1955, p. 161-198) of Boulanger's manuscript "Anecdotes de la nature" where he referred at great length to the morphology of the Marne river. He pointed to the magnificent and almost vertical amphitheatre between Meaux and Ferté-sous-Jouarre and explained that this phenomenon was produced by an ancient torrent, much larger than the present Marne, which when encountering a resistant mountain produced a large gap and carried away much sediments. While Boulanger thus gave descriptions of features along meandering rivers such as the change of direction of rivers when encountering obstacles—an idea which we shall find again in De Luc and Desmarest—he mainly stressed destruction along riverbanks, flooding and accumulation of sediments, high eroded cliffs, isolated mounts and hills in the plains, that is

features which he attributed to the effects of violent torrents after the irruption of subterraneous waters at the time of the Deluge. The lands which once connected these isolated mountains and cliffs exist no longer because they were eroded while whole civilizations were wiped out (Hampton, 1955, p. 163-172). Boulanger's intentions were after all not to explain processes of present-day rivers but the history of ancient destruction of lands and mankind by torrents. But in order to unravel that history, and no matter how he interpreted what he saw, he nevertheless had to follow the approach of modern geologists and describe features of meandering rivers.

Boulanger's response to the question "Where did all the waters come from", was his belief that oceans and continents are equally distributed around the globe into a marine hemisphere and a terrestrial hemisphere. He thought that the earth's strata were highly elastic and that during the Deluge, extremely high tidal waves developed which chased all the waters of the marine hemisphere toward the terrestrial one so that the former became dry and the latter sank underneath the ocean. At a later stage, lands emerged again, evacuating the waters into their natural basins. Boulanger believed that there was plenty of water on the earth's surface to cover at least one half of the earth, that is the terrestrial hemisphere (article "Déluge", p. 800).

In response to the third question about the effects of the Deluge, he answered in respect to marine fossils, that if one accepts the theory that our lands were once covered by the sea, the waters of the Deluge are not necessary (p. 801). In regard to corresponding angles, he refuted the concept as follows:

> Bourguet and other naturalists after him have noticed that all mountain chains form alternating corresponding angles, a disposition which is a direct consequence of the sinuosity of our valleys. They concluded that these valleys are the ancient beds of currents of the sea which covered our lands and which nourished and produced marine organisms, the remains of which we discover in our lands. But if the bottom of the sea emerged from the waters, the ancient slopes and directions of currents have changed since. Why should the waters of our rivers and streams follow the same path as the ancient ocean currents since today everything is completely different and opposite to the ancient landscape so that what was once in a low position is now high up and vice versa? Do these present rivers not flow on new and different slopes? Is it not more reasonable and natural to believe that if the ancient seas and their currents left some imprints on their beds, these imprints must no longer be related to the present state of things and to the new form of continents? These questions must raise doubts about the origin of corresponding angles (p. 802).

The words "They concluded that these valleys are the ancient beds of currents of the sea" refer to the implication in Buffon's theory of ocean currents. To that theory, Boulanger opposed his own:

> Meandering valleys which form corresponding angles are along their course and in their ramifications so much related to the position of our mountain tops and our lands as a whole that we suspect that they are a natural effect of their situation above sea level and not the traces of ancient ocean currents. Our lands were since their emergence higher in their center than on the sea shores so that it was necessary that rainwaters and springs immediately started to carve a multitude of paths toward lower regions and the seas notwithstanding all the irregularities along their course. After the violent irruptions of springs and rainfalls at the time of the Deluge, the resulting torrents carved and enlarged these paths to the point as we see them today (p. 622).

The above shows that Boulanger's initial valleys were enlarged at the time of the Deluge and that the former began to be carved after the emergence of lands and not as Buffon believed on the bottom of the sea.

PALLAS' CRITICISM OF BUFFON'S THEORY OF THE EARTH

Peter Simon Pallas, born in Berlin but writing in French for the Royal Academy of Sciences at St. Petersburg, was critical of authors who "merely rely on a single or a few particular observations and causes from which they want to deduce all effects of nature, in other words, national prejudices, so to speak, or ideas proper to the individual sphere of knowledge are used to explain the structure of the entire earth according to local geology". "Buffon", said Pallas, "has judged mountains in general according to those found in France which consist mostly of strata which are nearly horizontal or which were merely disarranged by volcanic activity" (1778, p. 4-5; this refers to the German edition *Betrachtungen über die Beschaffenheit der Gebürge...* which is in all respects superior to the French essay published at St. Petersburg in 1777 as well as the French editions published in Paris in 1779 and 1782).

The above work contains Pallas theory on the origin of secondary and tertiary mountains and strikes me as a response to Buffon's theory of the earth. Pallas believed that all great mountain chains are composed of granite. He did not speculate on their origin but held that they were always above sea-level (p. 10-12). Secondary mountains were formed in the waters of the ocean and he suggested that they might have been lifted during a combination of earthquakes and tsunamis (p. 15-16). Tertiary mountains, composed of sands and marls, contain a multitude of plant remains, of bones of elephants and rhinoceros from India; the structure of these mountains shows destruction by water (p. 53-63). When describing the mountains in Asia, he said in regard to the concept of corresponding angles: "It is not in these high altitudes that any proof can be found for the theory by the philosopher Bourguet, repeated by the Count Buffon, in regard to corresponding angles in mountains. That idea encounters many excep-

tions in all granitic mountains and even in secondary ones" (p. 36). Pallas, however, did not say what these exceptions are.

Pallas, in his rejection of Buffon's theory of ocean currents and corresponding angles fell victim to the same prejudices he blamed in other naturalists, namely the influence of local geology on the formation of theoretical ideas. When he wrote his essay on the formation of mountains, he had already a theory in mind, first described in the Preface to the third volume of *Reise durch verschiedene Provinzen des Russischen Reichs* (1771-1776, Reprint 1967) where he studied the different rocks in the Ural Mountains. He stated that strata of sandstone containing petrifications of terrestrial plants, petrified wood, and animal bones had not been deposited by a calm sea but had been transported by a flood which invaded vast areas of land. His theory on the formation of tertiary mountains was confirmed when he found in Siberia, to the east of the Ural Mountains and north of the Altai chain, to the shores of the Arctic Ocean, an incredible amount of remains of animals and plants. In his essay on the formation of mountains he, therefore, stated that a great flood caused by underground fires in the Indian Ocean had rushed toward the north and deposited these remains (p. 78-80).

JEAN-ANDRÉ DE LUC'S OBSERVATION ON MEANDERING RIVERS

De Luc referred to the controversy on corresponding angles in one of his letters to the Queen of England (1779-1780, Tome II, p. 221-224):

> Before finishing this part on primitive mountains, I must refer to the alternatively opposed salient and reentrant angles which when announced by Mr. Bourguet made so much noise among naturalists that nobody doubted any longer that all mountains are the work of the sea. The following is an outline of his supposedly demonstrative phenomenon. Traveling in valleys, one encounters frequent turns of the road and where a salient angle forces the road to make a curve, one finds quite often a reentrant angle on the other side of the valley while the valley itself keeps more or less the same width. Mr. Bourguet having made this remark, and having considered the opposite banks of a meandering river which show the same opposition of salient and reentrant angles, arrived at the general conclusion that mountains were formed by ocean currents (p. 221).

De Luc seemed seriously interested in finding some natural laws for meandering rivers and wrote:

> ... these zigzags do not resemble the effects of running water very much. Indeed, this feature is more characteristic of waters which dig out a path than those which deposit sediments. A river while digging its bed will turn when it meets an obstacle

> and will erode the opposite side thus creating a meander. But one does not observe the same causes for such zigzags in currents on the bottom of the sea unless some mountains already existed there (p. 222-223).

Whereas De Luc noticed erosion but not deposition in meandering rivers—perhaps because he compared entrenched V-shaped valleys with meanders in floodplains and saw only downcutting and erosion in the first and deposition of pointbars in the second—he, nevertheless, pointed out the law of least resistance in meanders. Indeed, he said that if hypothetical ocean-currents encountered already formed mountains on the bottom of the sea, "and if they crossed them one way or the other, they would certainly do so in places which offer least resistance. Thus they erode riverbanks in the same way as rivers do" (p. 222-223).

The features of meandering rivers have been studied and named since antiquity but naturalists have not reached a conclusion on the issue why rivers meander and direct their energy from side to side. Modern geologists are split into different schools: one agrees with the law that rivers tend to take the course of least resistance when encountering an obstacle and therefore start to meander (Macar, 1946, p. 124; Stokes and Judson, 1968, p. 156; Press and Siever, 1982, p. 170), the other believes that the reasons for initial meandering is not fully understood (Putnam, 1964, p. 280; Tarbuck and Lutgens, 1984, p. 214). Holmes believed that meanders are the "direct consequence of the general principle that when one medium moves over another, the plane of contact tends to be shaped into a wave-like form". Therefore, a breeze over a smooth sea will cause ripples, wind over sand, a rippled surface, and the backwash of the sea waves running down the slope of a beach will create ripple marks (1965, p. 529). Maull (1958) had proposed even more reasons: change in velocity, in the substratum, in tributaries, in vegetation, or in winds; the movement of water in spirals or pulses, a surplus or a lack of energy in running water, and centrifugal forces (1958, p. 168-170). River meanders have been compared to surface-tension meanders in lab experiments and the conclusion has been reached that stream displacement may depend on centrifugal, gravitational, and resistive forces (Davies and Tinker, 1984, p. 505-512). Since the final laws have not been written for the satisfaction of all, it is all the more significant that in the eighteenth century, some of the best observers would try to find them.

In the Jura Mountains, De Luc found few corresponding angles and said: "Large valleys with the most visible salient reentrant angles cut, for the most part, across a mountain chain instead of following it. This announces destruction rather than construction" (p. 223). In this hint against the validity of Buffon's system, De Luc probably referred to transverse valleys, called "cluses" in the Jura Mountains, where rivers display the most spectacular salient and reentrant angles while they cut across mountain ridges. According to Buffon's theory, such rivers, if they were formed by the movements of the ocean, ought to follow mountain chains rather than cut through them. From this observation, De Luc concluded that corresponding angles in valleys

and mountains may well prove that they were once under the waters of the sea, but not that they were formed by the sea (p. 221-224).

In conclusion, while De Luc was skeptical of Buffon's theory, he offered nevertheless some constructive and fairly objective criticism on meandering valleys. His own theory included the idea that primitive and secondary mountains were shaped at the bottom of the sea, not by ocean currents but by successive catastrophes including chemical processes and expandable fluids which destroyed the primitive mountains and formed the secondary ones (1780, p. 236-244). He spent much time and effort to refute Hutton's theory of the earth claiming that present mountains had not been uplifted but were formed during collapse of primitive mountains and that erosion by rivers is almost non-existent and thus powerless to erode mountains, to carry their materials in the oceans, and to form there new mountains (1809, p. 360-364). Since Hutton seemed a much more formidable adversary than Buffon, De Luc's attitude toward Buffon was little influenced by his personal theory. In regard to the understanding of meanders, he noticed pertinent geological features and deduced some natural law.

HORACE-BÉNÉDICT DE SAUSSURE'S REACTION TO BOURGUET'S CONCEPT

In volume I of *Voyages dans les Alpes,* Saussure first refuted Bourguet's concept as follows:

> I shall demonstrate later on that Bourguet's observation on corresponding angles, which has made so much noise, is completely erroneous. It is true only in recently formed narrow transverse valleys, that is valleys which were shaped by rivers and torrents since the retreat of the waters or during the retreat itself. Large longitudinal valleys, however, exist ever since mountains were formed. They are the only ones to be considered in a general theory. These valleys often show successive swellings and narrowings, namely the contrary of corresponding angles. To find the key to the theory of the earth in regard to the direction of currents in the ancient ocean where mountains were formed, we must inspect the direction of inclined bedding planes with the exception of a few particular cases where beds diverge from the norm. I believe to have been the first to observe the general law and importance of this phenomenon (vol. I, p. 511-512).

Although Saussure refused at the end to give a theory of the earth, it is evident from the above that at this point he had already formulated some ideas about how mountains were formed, apparently in the ocean. His attitude toward Bourguet's concept was, therefore, highly influenced by his own theory of mountain-building and by his concept of transverse and longitudinal valleys.

Saussure's embryonic ideas on mountain-building run through the four volumes without ever reaching a conclusion. He accepted the Wernerian idea that the sea once covered the surface of the earth and formed by its deposits and successive crystallisation first the primitive mountains and then the secondary ones and that the material of these mountains was deposited in horizontal and concentric layers (vol. II, p. 339). He could not decide, however, on how mountains were uplifted saying, at one point, that a violent tremor shook the earth and caused the rupture of large cavities and rocks (vol. I, p. 151), or, that fire or elastic fluids broke the crust and that during that process primitive mountains were pushed upward into a vertical position together with secondary mountains leaning against them. The explosion of elastic fluids broke and emptied underground chambers into which the waters rushed at great distances (vol. II, p. 339-340). In the fourth volume, he proposed the idea of "refoulement" (horizontal thrust), thus departing from De Luc's idea of elastic fluids (vol. IV, p. 183).

After his formulation of a theory of the earth in the second volume, he referred again to the "famous observation by Bourguet" of corresponding salient and reentrant angles and said that it was believed on the basis of this observation that valleys were carved by ocean currents. Valleys seen from the Cramont, however, contradicted this assumption, he said. In fact, they usually abut against a high mountain or a mountain pass and were, therefore, not carved by the sea but rather during its retreat or afterwards by the waters of snow and rain (vol. II, p. 340-341).

According to Saussure, longitudinal valleys—the only ones to be considered in a theory of the earth—were formed at the same time as mountains. The Rhône valley, for instance, was one of the largest. In order to form it, he said, the central chain of the Alps had to split along its length into two chains, one to the north, the other to the south. The first includes the Gemmi and the mountains of Grindelwald and Grimsel, the second the mountains above the Vallée de Bagnes, of S. Plomb (today Simplon), and of Griés (vol. I, p. 507-508). Other examples of longitudinal valleys are the valley of Chamonix which he thought to be an "ancient surface of the earth's crust" (vol. IV, p. 183), the Allée Blanche, the valleys of the Thuile, of the Great St. Bernard, and the Doire (vol. II, p. 341-342). Longitudinal valleys lie parallel to the general direction of the Alps and abut against high mountains or mountain passes. Transverse valleys, on the contrary, were shaped by rivers and torrents since the retreat of the waters or during the retreat itself. They are perpendicular or oblique to great mountain chains as, for instance, the Arve or the Giffre (vol. I, p. 510).

Saussure's notion of a "retreat" of waters was connected with his misunderstanding of "glacial deposits" in the neighborhood of Geneva, on the Salève, in the Arve valley, and on the foot of the Jura Mountains facing the Alps. He thought that after the uplifting of the Alps, a "débacle" took place when huge and violent rivers rushed toward distant opened abysses. When these waters decreased, they flushed the excavated valleys of mud and debris and left behind huge boulders and other solidly anchored material (vol. I, p. 151-152).

Neither Bourguet nor Buffon had described how tributaries enter meandering rivers. In fact, Bourguet merely described narrow mountain valleys or a "cluse" in the Jura Mountains where no tributaries flow into the main stream. Saussure, however, looked at the intricate network of rivers, in particular in "young" mountains, in order to contradict the theory of ocean currents. He observed that principal rivers are continuously cut by tributaries which receive other tributaries (vol. II, p. 342). This, he said, is best shown on a map where all valleys correspond to rivers which descend from some mountain and enter a main stream more or less at right angle, but not in pairs. "They resemble the branches of a tree which are implanted in the trunk in an alternating fashion so that each small stream enters the main river facing a mountain" (vol. II, p. 343). He concluded, "The concept of corresponding angles is neither universal nor true. It merely proves that valleys are either produced by fissures or separation of mountains or that they were shaped by torrents and rivers which run there presently..." He added, however, that he did not pretend that erosion and rainwater alone produce valleys: tilted rock layers show that other reasons exist (vol. II, p. 342-343).

It is evident that Saussure's reaction toward the concept of corresponding angles was highly influenced by his ideas on the origin of longitudinal valleys and mountains so that he overlooked meandering rivers such as the Arve because the Rhône valley seemed much more important to his theory. He nevertheless abstained at the end from giving a theory of the earth which he replaced by a list of future topics of research in the last pages of his book. It is significant that the concept of corresponding salient and reentrant angles is still included in that list. He asked that 1) salient and reentrant angles be checked in order to find out whether on the opposite side of an angle or wall of a mountain, another wall or mountain forms indeed a reentrant angle, or if, on the contrary, valleys show narrowings and swellings but not corresponding angles. 2) He wanted to know whether opposite mountains show analogies in height, shape, inclined faces, layers, and material. The answers to the above two questions might decide whether a valley was produced during rupture and separation of mountains or not. Finally, Saussure asked again to check whether tributaries of rivers are similar to the branches of a tree, namely whether they arrive in pairs or in an alternating fashion (vol. IV, p. 493-494). These requests show that Saussure's refutation of Buffon's claim on the correspondence of angles as representing the key to the theory of the earth remained incomplete.

JEAN-CLAUDE DE LAMÉTHERIE'S CRITICISM OF BOURGUET'S THEORY

In his discussion of theories of the earth, Lamétherie said that most naturalists agree that at one time or another the earth had been covered by waters, but that they disagree on how mountains and valleys were formed on the bottom of the sea. Some recognize that valleys may have been shaped by running water since they are still

formed today by the same cause. Bourguet, after Woodward, based his opinion on the regularly displayed salient and reentrant angles on the edges of valleys and concluded that great ocean currents may have excavated valleys with corresponding angles (vol. III, p. 340-345).

In response to Bourguet's concept, Lamétherie argued that running waters do not have the strength to achieve such effects as building mountains and valleys. Indeed, ocean currents, at a certain depth, have little strength except in preexisting valleys such as straits where their velocity is great between islands. He agreed that some large rivers display salient and reentrant angles in plains. But in primitive mountains, valleys show no such regularity because at the site where a corresponding reentrant or salient angle should exist, we find a new valley. Lamétherie referred here to Saussure's objection to the theory of corresponding angles and his belief that all main rivers are entered by tributaries and display a dentritic drainage pattern. Lamétherie also accepted Saussure's argument that longitudinal valleys such as the valley of Chamonix are closed at both ends and were, therefore, not shaped by ocean currents (vol. III, p. 348-350). Lamétherie shared Saussure's belief that primitive mountains and valleys were formed at the same time. He and Saussure differed, however, in their interpretation of the formation of these mountains and valleys.

According to Lamétherie, primitive substances crystallized in the same manner as salts and formed large groups of mountains of various elevation. As between groups of crystals, voids exist between large groups of mountains. These voids form the valleys of primitive landscapes and have no more regularity than the voids themselves (vol. III, p. 4-6). He believed that substances first to crystallize (feldspar, tourmaline, quartz, hornblende) formed granitic mountains. Micas, magnesium-rich and metallic substances remained longer in solution and crystallized later into gneisses and schists ("granits feuilletés"). These deposits would intimately adhere to primitive mountains thus following exactly their direction and their slope. The formation of secondary and tertiary mountains (limestones, phosphates, gypsum, schists, bituminous earths) occurred also by crystallisation after the primitive mountains had undergone much erosion, denudation, and alteration of their summits. Secondary and tertiary mountains, said Lamétherie, formed mountains and valleys entirely molded over primitive mountains (vol. III, p. 6-47).

While Lamétherie admitted that some mountains and valleys had been formed by volcanic activity, by rivers, by sinking, by uplifting, or by contraction, he stated that all these causes had very limited effects. The main cause for the formation of mountains and valleys is crystallisation of primitive and secondary mountains. The first can be recognized by continuous layers which display no visible fractures but can be tilted into vertical position, the second have discontinued layers which may have been disrupted by sinking, uplifting, volcanic activity, or the action of currents (vol. III, p. 104-105).

If ocean currents had indeed carved all valleys, said Lamétherie, they would have done so in cutting through entire mountain-chains. Instead, all large valleys originate

from mountainous centers in various continents. Furthermore, had valleys indeed been carved by currents, the Cordilleras in South America would be crossed by rivers, and in Asia, currents would have opened valleys on both sides of the continent. In the Alps, or the Rhône valley in particular, currents would have crossed mountain chains and penetrated into the valleys of the Rhône, the Danube, or the Pô (vol. III, p. 352-353).

Lamétherie had even more large-scale objections and said that if all valleys had been carved by currents, what would have become of all the removed sediments? Where would these have been deposited?: "Let us consider the mountains in America, on the one hand, and those of Africa, on the other. Let us suppose that the Atlantic Ocean was carved by currents. The space between the two mountain chains would thus have been excavated. But where would the enormous quantity of sediments, allegedly once filling the empty space, have disappeared? (vol. III, p. 355) After all these objections against Bourguet's or Buffon's theory of ocean currents, he concluded that the existence of running water demands preexisting valleys, and, therefore, mountains (vol. III, p. 355).

Lamétherie's criticisms were based on his theory of crystallisation of primitive landscapes. He even saw in the reciprocal angles of valleys a possible sign of their having been formed by regular or irregular crystallisation (vol. III, p. 351). This interest in theory rather than observation made him little inclined to study meandering rivers per se.

NICOLAS DESMAREST'S FINAL REJECTION

When Nicolas Desmarest first referred to corresponding angles in 1757, he objected to the observation of intersecting mountain chains in Peru made by Father Feuillée: "He should have searched for observations in other countries... thus he would not have restricted himself to fruitless considerations of final causes. The idea of the direction of mountain chains, combined in a different way, has led to the discovery of corresponding angles by Mr. Bourguet". Desmarest then stated noncommitally that, in general, the exterior form of mountains is markedly related to the disposition of layers which contribute to the interior structure of mountains and that corresponding angles are more frequent and pointed in deep and narrow valleys (*Encyclopédie* of Paris, 1757, vol. VII, p. 616).

Almost fifty years later, Desmarest returned to the concept of corresponding angles and asked the following questions: 1) Does this phenomenon occur as constantly as claimed by Bourguet and Buffon? 2) If not, under what circumstances? 3) Could ocean currents have shaped such a correspondence between the two sides of valleys as proposed by Buffon? 4) How does the action and the effect of running water in a river on the surface of the earth differ from the action and the effects of running

water in a mass of water similar to ocean currents? 5) What are the real features of corresponding angles and the evolution of their opposite shapes? (1803, vol. II, p. 590-591).

He answered that corresponding angles exist only in rivers with restricted and narrow channels which respond best to the surges of running water. In very large rivers, these reciprocal influences are diminished or lost. Salient and reentrant angles occur only in meandering rivers. Desmarest stressed that rivers do not meander on steep slopes but only when they reach a more gentle slope. With their velocity diminished, they deposit sediments instead of transporting them which create obstacles. The river, therefore, makes a detour toward the opposite bank which is eroded and eventually destroyed. He specified that after great floods, rivers transport much sediments which force them to meander and by the continuous erosion of reentrant angles, riverbeds are eventually enlarged. He noticed that in many entrenched valleys the correspondence of salient and reentrant angles is reduced to a simple parallelism of riverbanks; in other valleys destructive forces acting upon the edges of meandering rivers have disfigured their original shape (p. 591-593).

Most of Desmarest's descriptions of meandering rivers are modern in the sense that they are entirely based on facts. He was not able to interpret all these facts, but as De Luc before him, he believed that rivers start to meander when they encounter some obstacle. He understood erosion and deposition along meandering rivers and the transient nature of their shapes. He stressed that these are the real circumstances which shaped corresponding angles and "instead of seeing these shapes everywhere, Bourguet and Buffon should have described, as we just did, the real circumstances when they occur in our valleys" (p. 591).

Desmarest's response to Buffon's theory was hampered by his lack of knowledge of the ocean floor so that he was unable to answer his own questions on the difference between meandering rivers and ocean currents. He argued, however, intelligently against Buffon's method of inquiry. He rejected the idea that ocean currents display alternating angles similar to those in our present valleys as if "these corresponding sinuosities had been prepared on the bottom of the sea by nature which intended them in advance for the circulation of rainwater after the retreat of the sea..." (p. 592). Desmarest objected, furthermore, to Buffon's theory in general: "Mr. Buffon considers all these hypotheses as forming a body of proofs, as reliable as they are in physics. He presents a theory based on what he is willing to give as facts and which he thinks are independent of any hypothesis if one has only the courage to believe in it as he believed in the general concept proposed by Bourguet without previous inquiry... (p. 593).

Desmarest understood that rivers and valleys undergo great changes and criticized Saussure—without mentioning his name—for his belief in the fixity of mountains and valleys after their formation and for refuting the concept of corresponding angles:

> These angles were categorically refuted because they were not encountered in the great mountain chains which separate the Canton of Bern from the Valais, on the one hand, and the Alps which separate the Valais from Savoy on the other, both mountain chains serving as limits to the Rhône valley. But one did not notice that even if these alternative angles existed, the later work of the waters, flowing abundantly in lateral rivers and merging with the Rhône, would have destroyed these shapes. One did not notice either that these alternative angles were neither begun, nor destroyed in these large concave valleys which were eroded by torrential waters (p. 592).

In short, Desmarest's rational description of meandering rivers is not only close to modern ones, it is also crucial for the evolution of a concept. He showed that corresponding angles do not owe their origin to some apparent symmetry in mountains nor the action of ocean currents but that salient and reentrant angles are merely the product of running waters which erode the concave side of riverbends and deposit on the convex side. Since salient angles in large rivers often correspond to large gently inclined surfaces (pointbars), he proposed to call these features "plans inclinés" (inclined planes); and since reentrant angles usually form cliffs, he proposed the term "bords escarpés" (cliffs or steep banks) (p. 593).

CONCLUSION

Between 1729 and 1803, an abstract concept of corresponding angles in mountains was changed into a realistic description of meandering rivers. Whereas Bourguet was actually talking about entrenched meanders, he, nevertheless, saw only the symmetrical shape of corresponding angles in mountains as proofs that our earth received its present shape by the various movements of terrestrial rotation during the short time of the Deluge. Buffon interpreted corresponding angles as proofs that ocean currents had shaped mountains and valleys on the sea floor during a long period of time. Since he could not see such mountains being built, nor their intervening valleys displaying corresponding angles, he inferred from maps by Philippe Buache and Luigi Ferdinando Marsigli, as well as from Benoît de Maillet's description of the sea floor, that Bourguet's corresponding angles observed in mountains must necessarily also exist on the bottom of the sea since all running waters follow the same rules. He did not say that present-day rivers flow in ancient valleys carved by ocean currents, but the implication was criticized by De Luc, Boulanger, and Desmarest.

For modern readers, it seems obvious that Bourguet was not talking about ocean currents and that his mountains were formed at the time of the Deluge and not over a long period of time. All Eighteenth-Century French speaking naturalists, however, merely mentioned the action of ocean currents when they mentioned corresponding

angles. I believe that they found Bourguet's cosmogony too abstract and that they used, therefore, Buffon's ocean currents which are well-explained and easily visualized. The first drastic change of Bourguet's concept thus occurred in Buffon's interpretation when he replaced an abstract concept of final causes with a theory on present-day causes, namely ocean currents.

Pallas, Saussure, and Lamétherie merely refuted Buffon's theory of ocean currents without mentioning present-day meanders. They all had some theory which tried to prove with a few general laws that great changes had occurred in the past. Meanders seemed, therefore, of little importance.

Boulanger, De Luc, and Desmarest refuted Buffon's theory of ancient ocean currents with a comparison to present-day meandering rivers at the surface of the earth. Boulanger, as engineer, carefully noticed the names of places and rivers and his study of the morphology of the Marne valley is probably one of the most vivid and impressive of his time. His catastrophic view of diluvial irruptions of springs and violent torrents, which wiped out whole civilizations, made him mostly aware of the destructive elements in meandering rivers such as the erosion of riverbanks into high cliffs, flooding and accumulation of sediments, gaps in mountains, and isolated hills and cliffs in the plains. All these features, he believed, were the effects of violent torrents during the last Deluge. De Luc observed present-day rivers in the Alps and in the Jura Mountains and arrived at the conclusion that rivers start to meander because they flow in the direction of least resistance. This point is still being debated among modern geologists. Desmarest's description of meandering rivers came closest to the modern ones. He saw erosion of cliffs on the concave side and deposition on the convex side. He understood that rivers are transient features and that meandering rivers may destroy earlier valley forms. He proposed a new vocabulary calling salient angles (today's pointbars) "plans inclinés" (inclined planes) and reentrant angles (today's cut bars) "bords escarpés" (cliffs). Desmarest alone among his contemporaries seems to have observed meanders without any preconceived idea.

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