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The Digital Atlas of Innovations: A Research Program on Innovations in Prehistory and Antiquity

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The Digital Atlas of Innovations: A Research Program on Innovations in Prehistory and Antiquity

The authors discuss the simultaneous appearance of technological innovations in three key technologies (metallurgy, wheeled vehicles, weighing systems) in the second half of the 4th millennium. This is done from a source-critical perspective because the innovations are discussed with the help of dynamic maps from the Topoi project *Digital Atlas of Innovations*. Besides indications of diffusion gradients influenced by special research conditions, exceptional waves of innovation can be detected for all three technologies in the discussed period. These waves of innovation cannot, however, be generalized but have to be understood on the basis of the respective technology traditions and lines of development specific to local areas. Monocentric diffusion theories can be clearly disproven, local technology developments and their converging in certain centrally situated regions have to be assumed instead. Similarly, the transfer of objects and their *châine opératoire* can only be detected rather infrequently, while the adaptation to local socio-economic and environmental factors can be demonstrated.

Prehistory; Chalcolithic; Copper Age; Bronze Age; technological innovations; diffusion; mapping.

1 Introduction

Since the 19th century the history of technology started with the inventions in the Early States in Egypt and Mesopotamia. All inventions were made in the centres and then spread over the world into the peripheries. This kind of diffusionism was unsettled by the radiocarbon revolution which pushed back some innovations in time. Metallurgy was invented long before the ancient city states and the first evidences for wheel and wagon were found in a wide are from the Atlantic to the Persian Gulf.

Beside radiocarbon revolution the end of East-West bloc confrontation made new research possible understanding the interdependencies between Europe, Western and Central Asia and the Far East in the Holocene.

Under a layer of outdated assumptions it is possible to expose new empirical evidences for the innovations in toolmaking and craftsmanship but also ideologies which in many cases coined the live and dead of people until the 18th and 19th century. This has to be done in the perspective of a global history of knowledge to which archaeology can make a major contribution. The long durée and the global perspective unfold an explanatory power in the history of knowledge. It is one history of knowledge and all kinds of knowledge are of equal value. Now, the emergence, the transfer and transformation of knowledge can be traced over thousend of generations by archaeology.

2 The *Digital Atlas of Innovations* as a tool. Possible applications

Everytime when the world was measured anew, new maps were required. The Digital Atlas of *Innovations* is a new tool, an interactive, interoperable map connected to a continuously growing find database. For a long time, archaeology has been collecting the material remains of many innovations, from the first use of fire in the Paleolithic to the first use of pottery in the Neolithic to the invention of the screw in antiquity. Admittedly, the mapping of, in each case, the earliest evidence of great and small innovations already allows us to locate the technologies in the world. However, these maps often have only illustrative character. The Digital Atlas of Innovations, on the other hand, is a dynamic tool that makes developments and relationships identifiable. We will, of course, never find out where the wheel was invented. Therefore, the *Digital Atlas of Innovations* examines the earliest evidence of innovations over a longer period. That is the first 2000 years in the case of wheeled vehicles! The innovations are embedded into an examination of the long duration *(longue durée)*. It is the strength of prehistoric archaeology not only to look at such long periods of time on the basis of physical age determination, but also to be able to examine them precisely for short-lived booms.

An atlas consists of a wide range of maps. The scale of the maps is determined by the manageability when used. A world atlas offers an overview of the countries of the earth; in order to capture the geographical details of individual countries, on the other hand, one needs different atlases. The Digital Atlas of Innovations is not restricted by such limitations. It is a dynamic tool that makes it possible to change the scale of time and space and to continue creating new maps. With the aid of a timeline, all pieces of evidence for innovations can be represented in decades, centuries or millennia. The *Digital Atlas of Innovations* allows also to distinguish periods of increased technological innovations from those times in which no or very few changes can be recognized (Fig. 1). In the same way, innovative regions and innovation-hostile regions can be identified. It will be possible to determine which bodies of knowledge were, after all, available in individual regions or could have been available.

The Digital Atlas integrates the archaeological sources on several different levels and, in doing so, is able to represent different steps of a production chain. Therefore, it is not only possible to map the earliest evidence for a certain innovation on the basis of finds, but also to generate maps for different detailed solutions based on technological properties. The earliest use of silver can be represented on the basis of finished products, the cupellation on the basis of byproducts.

By trade or given as presents, objects can become widely distributed without the associated knowledge of their production being spread as well. The *Digital Atlas of Innovations* is, however, able to prove the distribution of formulas, in other words, hard technological knowledge, for example based on the characteristics of copper alloys (see below). It is also suited to represent ritual practices like sacrifices, for instance, on the basis of their remains in time and space. At the same time, a source-critical basis for the representation and discussion of the emergence and spread of technological knowledge is created in doing so. There is always the question in which archaeological contexts objects have been passed down (e.g. as a sacrifice) and under which conditions they have survived (e.g. wood in moors and deserts). This is also important regarding those artifacts whose material can be re-used regularly, like copper and silver: mostly those artifacts have usually survived that were consciously withdrawn from the recycling loop by depositing them in graves or hoards. Therefore, it is a given that the find contexts can be linked to the objects in the mappings.

It has to be stressed that the dynamization of the archaeological 'distribution map' allows us to recognize *new* relationships in time and space. The existing distribution maps show stages of innovations, defined by the respective scholar for different reasons. Often,

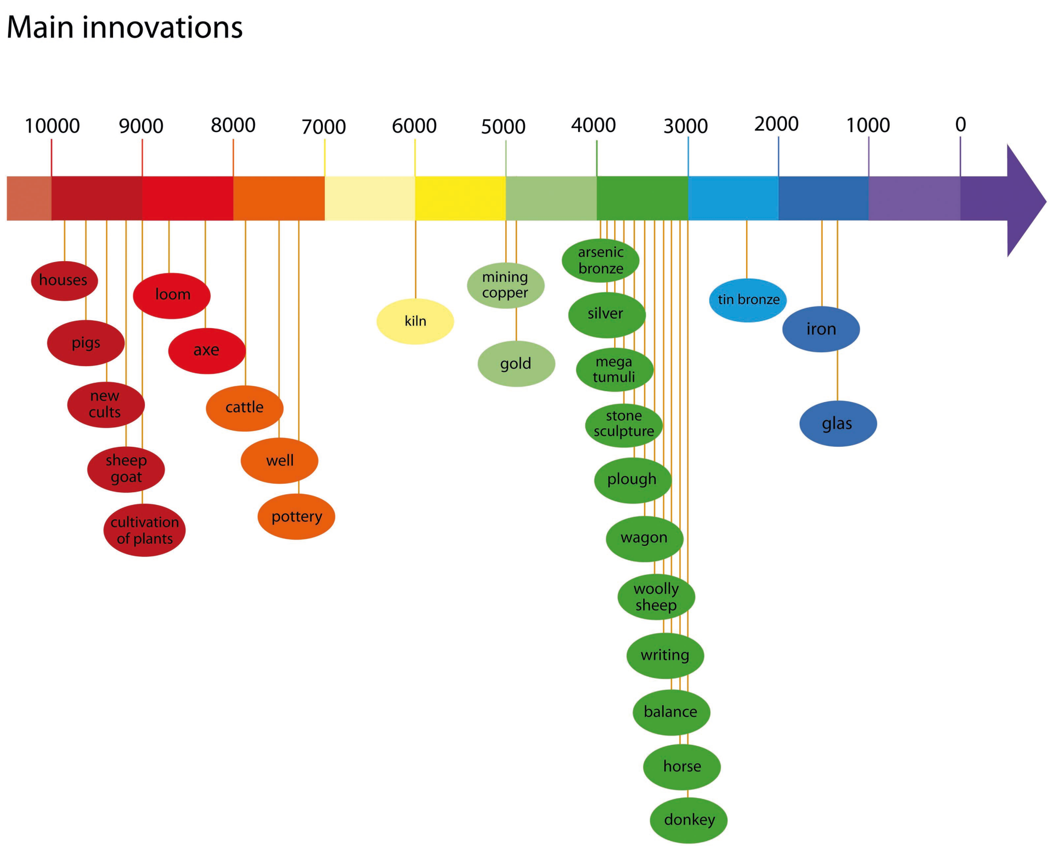

Fig. 1 | Overview of the taking effect of prehistoric innovations; not the first appearance is shown, but the wide-ranging use on the Eurasian continent.

these stages are (arbitrarily) assigned time marks. The *Digital Atlas of Innovations*, however, aims at reading the rhythms of development and periodizations in the maps. Therefore, new questions can be generated from the maps. The maps in the *Atlas of Innovations* are not the illustration of a statement, but a heuristic device on the basis of which new questions can be asked. They constitute the beginning of a line of thought. The map itself becomes an essential device to direct logically consistent lines of thought.[1]

3 Innovation and technology as a social phenomenon

Innovations are new and useful things.[2] As a result, earlier research often explained their spread with the help of a functionality paradigm. According to A. Toynbee, technologies are developed in order to solve challenges and problems in interacting with the environment.[3] The right amount of problems, i.e. a certain environment, finally leads to the kind of technological progress that was followed by the first states. U. Eco, however, has challenged this notion of innovation by critically considering the sources, asking whether

1 Eggers 1950–1951.

2 The *Duden* defines innovation as "planned and controlled change" ("geplante und kontrollierte Veränderung"), "introduction of something new" ("Einführung von etwas Neuem") and "realization of a novel, progressive solution for a certain problem" ("Realisierung einer neuartigen, fortschrittlichen Lösung für ein bestimmtes Problem"). Cf. www.duden.de/rechtschreibung/Innovation (visited on 01/06/2016).

3 Cf. Toynbee 1965, especially vol. II, "Challenge and Response".

innovations that have been interpreted as creative quantum leaps could not just reflect the absence of other serially produced counterparts. Furthermore, his and newer considerations show that the variation necessary for innovation is often accidental and emerges from the creative handling of known technologies.[4] According to this, an innovation is a creatively and newly arranged selection of known features which will be accepted if it fits into the society's repertoire of symbols.

Technological innovations already were an integral part of different primates' cultures, i.e. they are not an exclusive characteristic of human beings.[5] Especially artifacts, in other words, mechanizing innovations, can be archaeologically recorded, while innovations on other levels have to be inferred via analogies. The ability to implement almost continually new technologies in a social system is a characteristic of our culture – and has been since its earliest beginnings. At 3.6 million years, the earliest stone tools known at the moment are even older than the species *Homo*,[6] and this circumstance could be read to the effect that the use of stone tools by Australopithecus was an important factor for the human evolution. Thus, technology made humankind.

Technology and society structure each other in a network of relationships on different levels and over long periods of time: For such a process, however, technologies also have to be compatible with the social system in which they are intended to work.[7] Since existing technologies can be degraded by the emergence of innovations, an innovation does not suddenly lead to an improvement of living conditions.[8] For this reason, too purposeful an understanding of innovation is only useful to a limited extent. For example, innovations can be due to the marking of cultural characteristics and the targeted search for cause-effect principles.[9] Even if the invention of new technologies is often associated with individuals, their development is far more complicated. Technological innovations draw on elements of known technologies and improve these or combine long-known aspects in a new way.[10]

Innovations spread or are rejected precisely because they are socially relevant. This happens, for example, when people that are considered exemplary use them or when the non-use as a deviation from given standards leads to social sanctions.[11] As a consequence, the imitated group can see themselves forced to define new standards which produces further innovations.[12] In this way, the consumption of innovations can develop its own dynamics that is fed by the pursuit of social distinction.[13] The taking up of an innovation is, however, also a risk since the desired distinction is not guaranteed, and people without access to the technology can subsequently lose their status. Moreover, an open society that is prepared to allow innovations and understand their social value is a basic condition. Therefore, innovations are particularly promoted by social fringe groups that risk a loss of status more easily.

The work of E. M. Rogers, who believed to have identified five aspects that decide over the acceptance of innovations, is instrumental for researching innovations in modern times.[14] When an innovation convinces, the adaptation process begins in which the innovation is used by an increasingly larger group – this is diffusion and can be graphically

4 Eco 1989; Eco 1990; Eco 1994. Cf. also the contributions in: Hallam and Ingold 2007.
5 Waal 2002.
6 Baales 2006, 53–54. Cf. also Baales 2012.
7 Rammert 2007, 19–24.
8 Schumpeter 1961.
9 Rammert 2007, 20.
10 Basalla 1989.
11 Tarde 2008.
12 Elias 1976.
13 Torstein 2009.
14 Rogers 2003, 15–16.

represented as a sigmoid curve in a coordinate system with the users on the y-axis and time on the x-axis. Since the archaeological sources record innovations only when they have already been adopted, it is almost impossible to document the invention and the early stages of the innovation archaeologically. During this diffusion, the innovation has to be communicated; this can usually be tracked well on the basis of the archaeological sources.

Although a number of modern consideration can also be applied to prehistoric and ancient societies, there are specific features that are hardly taken into account by modern innovation research. For example, the mastery of the whole production chain, including the sourcing of raw materials, their preparation and processing, is necessary for a permanent adoption of innovations. In the case of wheel and wagon, the general availability of wood and the mastery of woodworking is certainly a reason for the rapid and far-reaching spread. In contrast, the production of complicated metal tools obviously remained limited to a few regional centers.

3.1 Archaeology and technology

Prehistoric societies invest a significant part of their time in the modification of their artifacts. Besides the obvious improvement of tools, there can be a number of reasons for this. In an ongoing process, old artifacts are abandoned and new ones introduced. It is thanks to this fact that C. J. Thomsen's[15] division of prehistory into a Lithic, Bronze and Iron Age is, in principle, still valid today. W. F. Ogburn has postulated the temporal primacy of the technological development over the social development, coining the term "cultural lag".[16] According to this theory, technology develops more quickly than society, so society continually has to adjust to the conditions caused by the new technologies. V. G. Childe deduced the indeed great importance of technology from archaeological finds, but also showed how certain forms of society enable the generating of new technologies in the first place.[17] With this, he overcame, at least for prehistoric times, Ogburn's postulate.[18]

Only recently, the necessity of certain technological and social conditions has been increasingly pointed out in archaeology and their existence emphasized as vital for the spread and acceptance of innovations.[19] The history of sciences and technologies as a field of work has existed for some time, however.[20] An archaeology of innovations is not a matter of applying concepts worked out on the basis of other data to the finds, but to review these concepts with the aid of archaeological sources and to develop archaeological innovation research. Archaeological and historical sources offer, despite all their specific shortcomings, good conditions to examine the interplay of technology and society over longer periods of time. Due to their temporal depth, they are able to track the individual elements of which a technology is composed and they grant an insight into long formation processes of technology, and the willingness of societies to accept innovations and its consequences.[21] The understanding of the development, introduction and spread of technologies, and of the resulting social processes in prehistoric and ancient times is certainly in its very early stages and remains a research field that still has to be established, but possesses areas of contact with the history of technology of antiquity,[22] the Middle

15 Thomsen 1836.
16 Ogburn 1937.
17 Childe 1937.
18 Childe 1951; Strahm 1994.
19 Burmeister and Müller-Scheeßel 2014; Eichmann and Klimscha 2011; Hansen 2011.
20 Serres 1998.
21 Cf. e.g.: J. Müller 2004; Hansen 2011; Primas 2007.
22 Schneider 1992.

Ages[23] and modern times.[24] The *Digital Atlas of Innovations* can make not only prehistoric and ancient innovations visible, but also those from later periods.

The social implementation of technologies, for example, is of vital importance in the spread of innovations,[25] while continuous innovations can permanently damage a society. Moreover, the adaptation and diffusion of innovation requires consent about its usefulness. Such consent can only be communicated, however, if those innovations which are still in the adaptation stage do not disturb the social system too much. Therefore, one would have to consider whether a long-term interchange exists in successful societies between periods in which innovations emerge in batches and periods in which the return to tradition helps a group stabilize the social reproduction again.

The ability of innovation is a feature of *all* human societies. Some societies succeed, however, in developing innovative technologies that result in dramatic changes. In the long term, innovations possibly bring about a measurable improvement of living conditions (lower child mortality, increase in life expectancy). In the short term, however, dramatic worsening is possible, too,[26] since technologies are interwoven with social infrastructure in many and varied ways. This network is disturbed by innovations so that a society which is continually changing is soon confronted with social problems: Because missionaries distributed steel axes among adolescents, women and children of the Australian Yir Yoront in the early 20th century, the traditional stone adzes lost their function, not only as a tool, but also in religious contexts and as a status indicator of mature men. With this, the power basis of those groups controlling the distribution of stone adzes immediately collapsed, and steel axes became necessary to assert one's social position. As a consequence, men forced their wives into prostitution in order to get steel axes, and new exchange systems developed revolving around steel axes.[27] The steel axe as part of another world did not, however, colonize the Yir Yoront because more trees could be cut down or this could be done faster, but because how their society valued axes.

3.2 Innovation cycles

Periods in which innovations induce further innovations and permanently change a society have been called "hot" periods by various archaeologists[28] following C. Lévi-Strauss[29] as opposed to "cold" periods. In the "cold" periods, a society attaches great importance to constancy and stability and is, therefore, less innovative. This insistence on traditions can indeed be advantageous under certain circumstances.[30] If this interpretation is true, important innovations appear bundled together and are distributed as a 'package'. This, in turn, could mean that the technological differences visible today between archaeologically surviving societies can be traced back to the conditions for communication. Thus, groups with intensive long-distance connections would have had an increased chance of gaining knowledge of innovation packages. Archaeology itself seemed to deliver the evidence since the diffusion of innovations on the Eurasian continent from east to west is considerably less hindered by different climate zones and mountain ranges than is the case between South and North America or throughout Africa.[31] Beyond the Ne-

23 Popplow 2010.
24 König 2009.
25 Bijker, Hughes, and Pinch 1989.
26 Schievelbusch 2000.
27 Sharp 1952.
28 E.g.: Bernbeck 2004; Vandkilde 2007.
29 Lévi-Strauss 1972; Lévi-Strauss 1973.
30 Palmer 2010.
31 Harris 1977; Diamnond 1997.

olithic transition, however, this concept reaches its methodological limits. For example, the spread neither of wheeled vehicles nor of copper metallurgy can be explained only by the conditions of the natural environment.[32]

4 Wheel and wagon – facets of an innovation

There is no need, according to general conviction, to reinvent the wheel. It seems so fundamental that a society without the wheel is difficult to imagine. So far, 2421 pieces of evidence of pre- and protohistoric wheels have been cataloged in our database (Fig. 2).[33] The majority of finds has been classified as "real-life objects", meaning they are parts of actually used wagons, while illustrations and models of wagons only account for about one third of the stock of finds. These finds come, in roughly equal shares, from settlements, graves and the art trade; some wagons have also survived as petroglyphs (rock art) and in hoards. The definition of the time interval from 4000 to 2000 BC makes it clear that the early wagons remain restricted to a triangle between central Europe, India and Siberia (Fig. 3). It takes about 1500 years until the wagon can also be traced in other regions. Looking only at the early wagons, it is apparent, too, that almost half of them are miniature wagons (or parts of them).

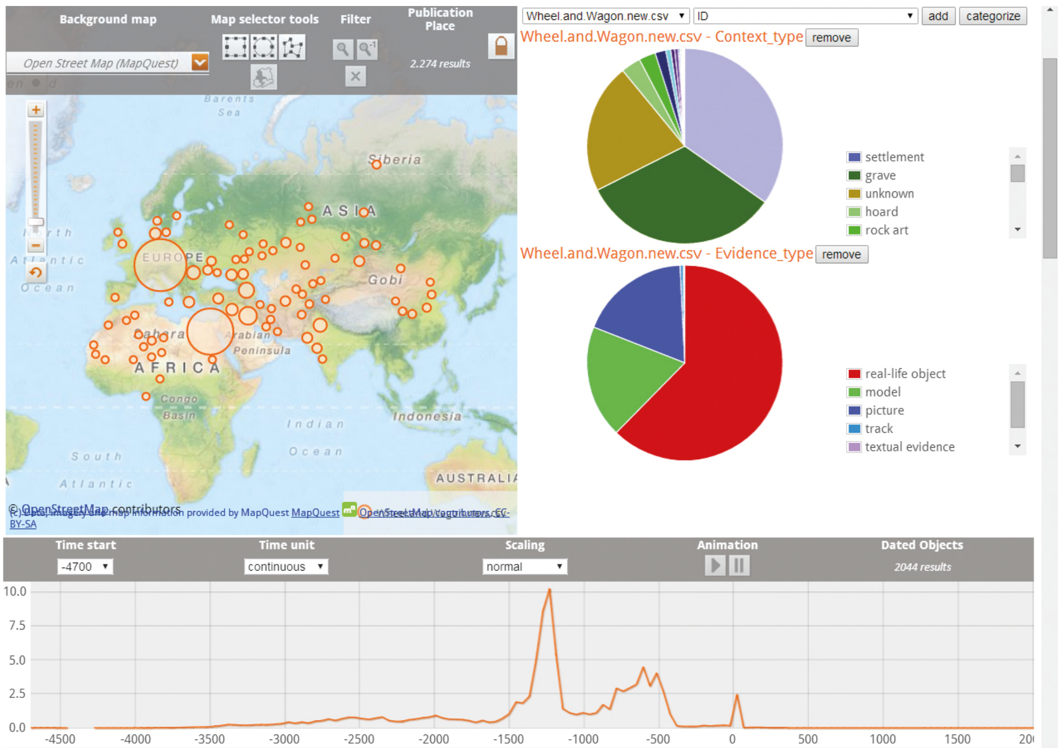

Fig. 2 | Wheeled vehicles cataloged so far in a query from the Digital Atlas of Innovations: [find_type=Wheel & Wagon; added categories: Context_type, Evidence_type; n=2044] and definition of a time interval and its application.

32 Cf. Burmeister 2004a (wheeled vehicles); Roberts, Thornton, and Pigott 2009 (metal).

33 So far, the project focuses on the wheeled vehicles of the 4th and 3rd millennium, so younger finds have not been systematically recorded. The significantly higher number of wheeled vehicles from the 2nd and 1st millennium consists of completely different types (e.g. state wagons, wheel pins, funeral wagons, chariots, etc.), which require different research questions.

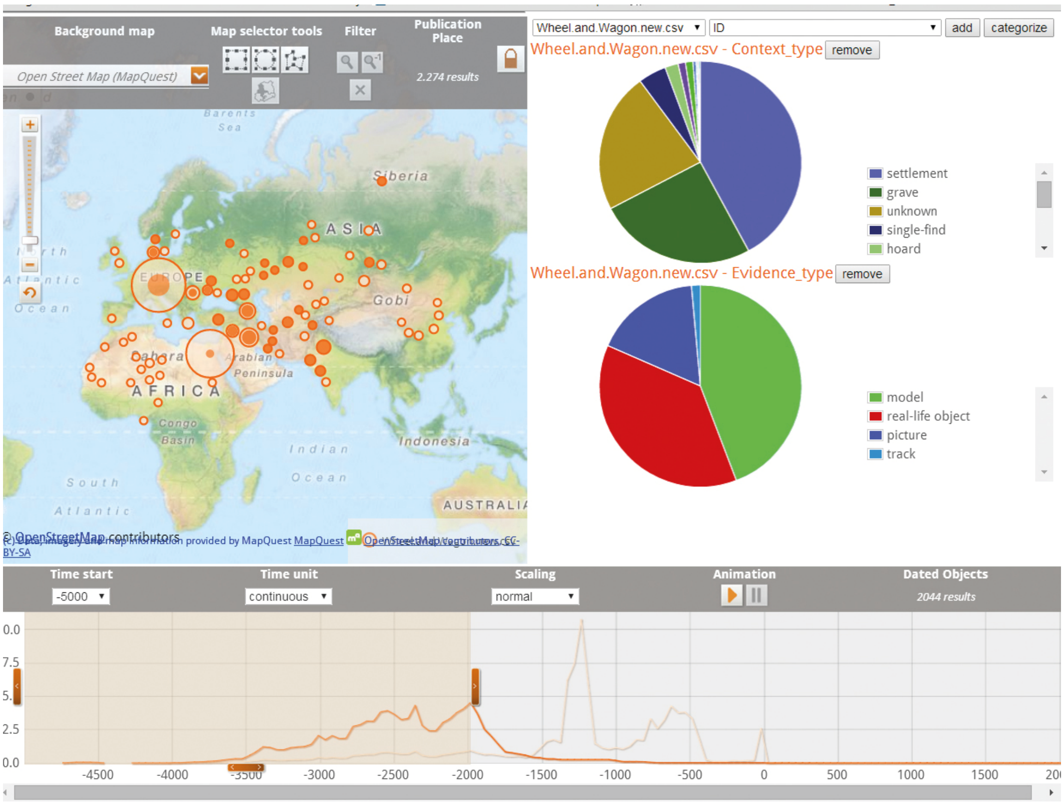

Fig. 3 | Wheeled vehicles cataloged so far in a query from the Digital Atlas of Innovations: All wagons between 5000 and 2000 BC are shown [find_type=Wheel & Wagon; added categories: Context_type, Evidence_type; time interval= -5000/-2000; n=2044].

Where and when, however, has the wheel been invented? In older model concepts, for example the diffusion of innovations theory, all technological innovations were developed in the centers of the early civilizations and then spread to the peripheries as far away as Europe. The invention of the wheel and many other key technologies was thought to have been located in Mesopotamia or Egypt and was dated to the end of the 4th or the beginning of the 3rd millennium BC.[34] With the calibration of radiocarbon dates and the development of chronological frameworks independent of typology, new perspectives have opened up, especially regarding the issue of innovation centers for certain technologies and their spread:

Around 1900, leading scholars still assumed that the Mesolithic in northern central Europe was simultaneous with the Bronze Age in Mesopotamia and explained the cultural divide between Mesopotamia and southern Scandinavia as the transfer of technologies and forms of organization from the Orient to foreign cultural environments.[35] V. G. Childe called the bundle of trade, fulltime specialization, division of labor and a multitude of technological innovations *Urban Revolution*.[36] He, too, assumed that the urban centers in the Orient were the starting points for the successive transfer of information via far-reaching communication networks. This is hardly surprising insofar as Childe also had no possibility at all to determine the absolute age of finds outside the early advanced civilizations other than via typological chain datings.

34 Cf. summary in Burmeister 2004a.
35 S. Müller 1905, 17–20.
36 Childe 1951.

Only when radiocarbon dating had been introduced it became possible to study the relationship between early civilizations and non-literate areas free from presuppositions. This has caused – as, for example, in the case of wheeled vehicles – the earlier model concepts of 'ex oriente lux' to come into conflict with newer hypotheses based on radiocarbon dates.[37] Nowadays, it is not possible to decide on the basis of the archaeological sources where and when the wheel was 'invented' because we see that it appears between Mesopotamia and northern Germany almost at the same time, around the middle of the 4th millennium.

The radiocarbon revolution of the last 30 years allows archaeology, for the first time ever, to determine the development of technologies more precisely in terms of chronology and to ascertain the spread of innovations in time and space. The Digital Atlas helps to qualify this statement since a query of all wheeled vehicles of the 4th and 3rd millennium, broken down according to their datings, plainly shows that modern scientific datings are clearly concentrated in central and northern Europe (Fig. 4). Therefore, it might be that the current finding is a research artifact caused by different dating methods. It cannot, of course, be proven that the finds in western Asia will again become earlier than the European wheels if radiocarbon dating is consistently applied. It is equally possible that future examinations will confirm the datings or outline more clearly a different zone, for example the Black sea region, as the earliest center.

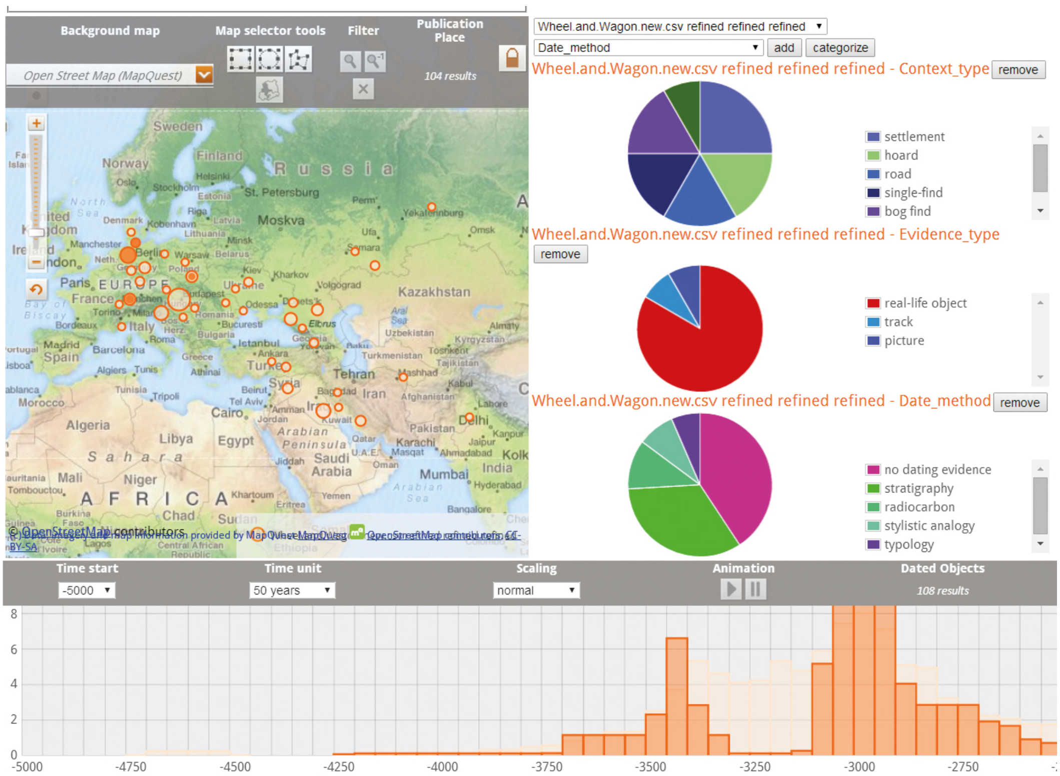

Fig. 4 | Radiocarbon dated wheeled vehicles of the 4th and 3rd millennium. Query from the Digital Atlas of Innovations [find_type=Wheel & Wagon; added categories = Context_type; Evidence_type; Date_method; time interval= -4000/-3000; n=108].

37 Renfrew 1970; Renfrew 1973.

This is suggested by structuring the same mapping according to the type of evidence category, 'real-life object', 'depiction' and 'model': Since models and pictures of wagons are usually not made of organic materials, they cannot be examined for their radiocarbon content – if they have not been found in a layer that can be dated in this way. While pictures of wagons, however, mainly occur in central Europe, Asia Minor, Syria, Mesopotamia and Egypt (Fig. 5), wagon models extend to the Indian subcontinent (Fig. 6).[38] Apart from a few exceptions in Mesopotamia and Palestine, on the other hand, finds of real wagons occur only in those areas where the soils allow the survival of wood or organic remains have a chance of survival in lakes and moors, for example in the circum-Alpine pile dwelling settlements, the moors of Frisia, Jutland and Sleswick, and in the tumulus burials in the northwestern Black Sea region and the Eurasian steppe region (Fig. 7).

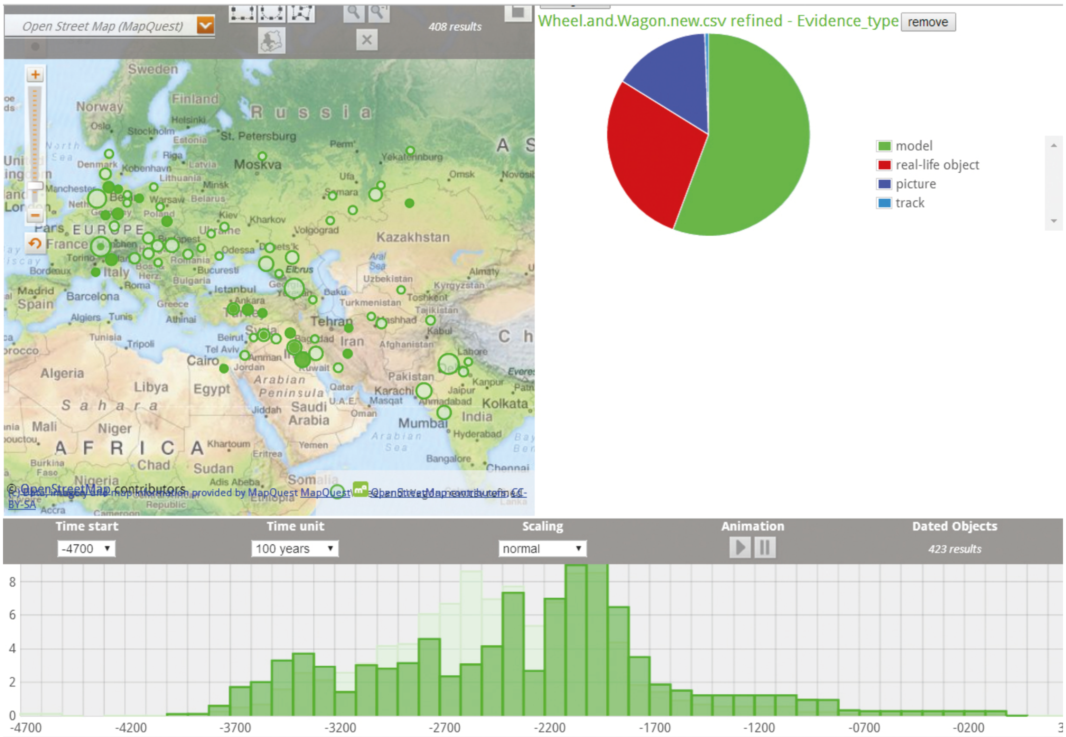

Fig. 5 | Definition of a time interval and its combination with an attribute field. The filled symbols show all surviving finds between 5000 and 2000 BC in the form of pictures [find_type=Wheel & Wagon; added categories: Evidence_type; time interval= -5000/-2000; n=423].

38 Cf. Kenoyer 2004.

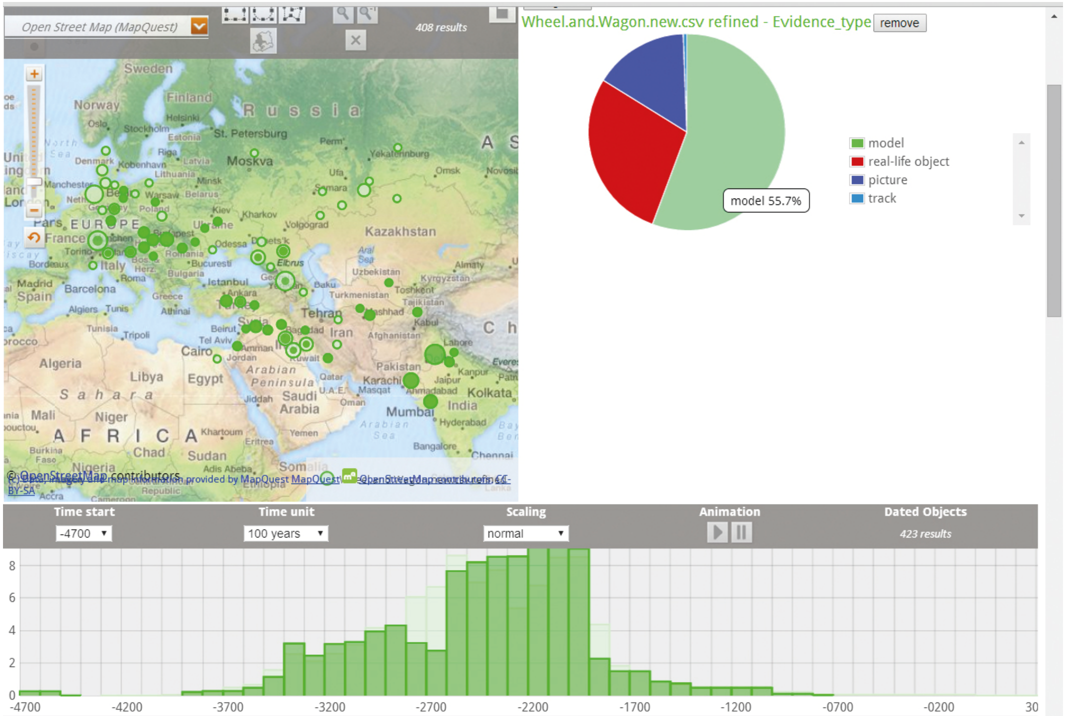

Fig. 6 | Definition of a time interval and its combination with an attribute field. The filled symbols show all surviving finds between 5000 and 2000 BC in the form of models [find_type=Wheel & Wagon; added categories: Evidence_type; time interval= -5000/-2000; n=423].

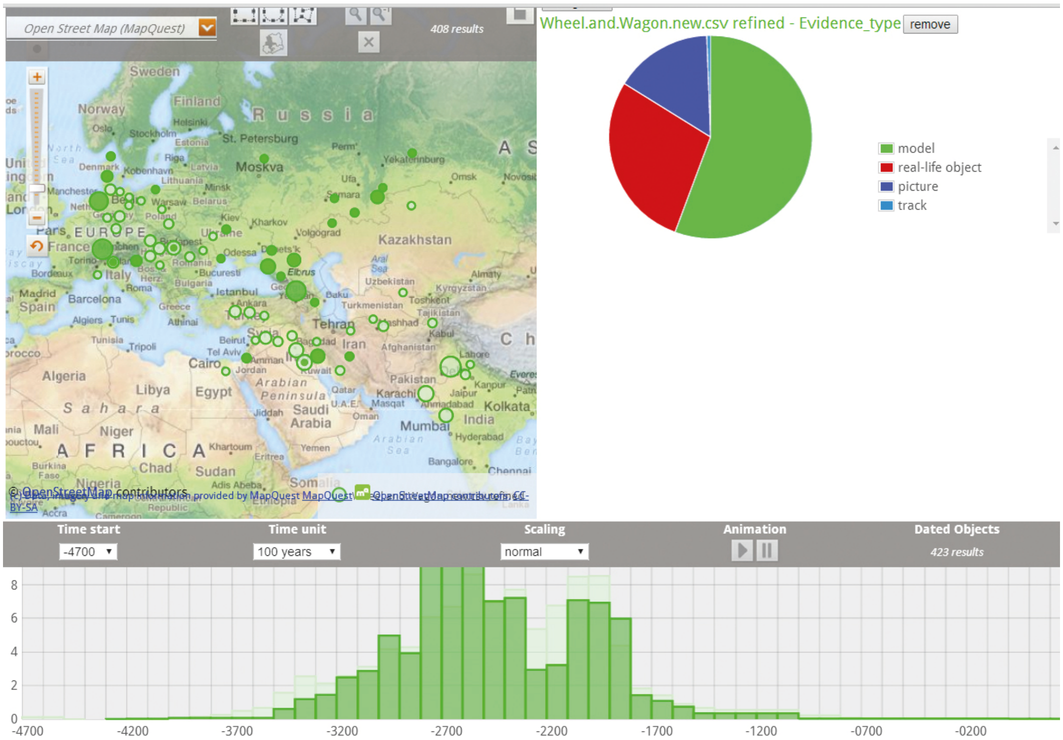

Fig. 7 | Definition of a time interval and its combination with an attribute field. The filled symbols show all surviving finds between 5000 and 2000 BC in the form of realia [find_type=Wheel & Wagon; added categories: Evidence_type; time interval= -5000/-2000; n=423].

4.1 The spread of wheel and wagon

Like in later periods, the development of new technologies in prehistory also seems not to have happened continuously, but in innovation batches.[39] After the fundamental innovations that led to the development of the farming economy and way of life ('Neolithic Revolution'), another overthrowing innovation featuring the mining of mineral ores, their processing and the casting of finished products was successful in the 5th millennium, laying the foundation for the future development up to modern industries. The 4th millennium was characterized by the spread of further key technologies over a wide area: wheel and wagon, the plough, the development of copper alloys, the use of lead and silver, the first production of copper daggers and swords, the domestication of the first equids, arsenic-copper alloys, and the wool sheep.[40] This innovation bundle is connected to new forms of representation, the burial of individuals under large mounds (tumuli) and the depiction of warriors on full-size stelae. Important innovations of this time like writing, the weighing scale and the pottery wheel remain, however, restricted to certain regions or the area of the urban civilizations.

This innovation horizon also includes Andrew Sherratt's theory of the *Secondary Products Revolution*: Animals were not bred anymore only because of their meat, but also because of their traction, their wool or their milk.[41] First of all, the seemingly simultaneous spread of plough and wagon, both bound to the traction of domestic cattle, was of central importance. This made the cultivation of larger areas and areas situated further away from the settlements possible which eventually allowed integrating the breeding of dairy cattle and wool sheep into the economical cycle in an appropriate way, too. The diffusion of these technologies started out from the Middle East where, above all, the layer IV of Uruk-Warka in southern Mesopotamia was vital.[42]

From a present-day perspective, it becomes apparent that individual innovations have to be dated clearly earlier than Uruk IV.[43] The beginnings of urbanization in northern Mesopotamia can be traced back to the late 5th millennium.[44] In Europe, however, it has to be clarified why many of the technological innovations mentioned at the beginning occur during the second half of the 4th millennium apparently as a package and why, in this time, actually important social changes can be observed in central Europe, but also in the Black Sea region and the Middle East.[45]

The distribution of the earliest evidence of wheel and wagon is concentrated in an interval from 3500 to 3300 BC (Fig. 8).[46] During this time, evidence of the use of wheeled vehicles is spread from the Middle East to northern Germany. Therefore, both a non-interdependent development and a very rapid diffusion process are possible.[47]

The rapid increase in finds that begins around 3400 BC can be well shown in a histogram featuring the datings of the known evidence of wheel and wagon. This representation also makes a comparison with the sigmoid curve known from innovation theory possible. E. Rogers used this curve to describe a successful diffusion process: In the course of time, more and more actors adopt the innovation until a critical quantity is reached and the innovation spreads very rapidly in a cascade-like manner.

39 Mensch 1975.
40 Hansen 2011.
41 Sherratt 1981; Sherratt 2004.
42 Sherratt 1993; Algaze 1993, and various contributions in: Frank and Gills 1993.
43 E.g. Klimscha 2013; Radivojević et al. 2013; Garfinkel et al. 2014; Roux and Miroschedji 2009; Rahmstorf 2006; Rahmstorf 2011; Rahmstorf 2012a; Mischka 2013.
44 Oates et al. 2007.
45 J. Müller 2004; Hansen 2011; Klimscha 2013 [2014].
46 Burmeister 2004b; Burmeister 2011; Burmeister 2012.
47 Cf. for this: Sherratt 1981; Vosteen 1996b; Vosteen 1996a; Bakker et al. 1999; Burmeister 2004a.

Fig. 8 | Indications of the use of wagons between 5000 and 3000 BC [find_type=Wheel & Wagon; added categories: Context_type, Evidence_type; time interval= -5000/-3000; n=108].

The takeoff stands out for the period of 3400 to 3100 BC. This means, however, that it has to be assumed that both the invention and the early period of diffusion happened in an earlier period. As mentioned above, five criteria decide on a successful diffusion:[48] The relative advantage compared to similar technologies, the compatibility with the particular social structure, the innovation's complexity, the opportunity to try out the innovation individually and, finally, to observe the innovation during its application. A check using these criteria helps illuminating possible reasons for the successful diffusion: The complexity of the wagon has probably to be considered relatively low because the turning moment had been known at least since drills and spindle whorls came into use in the early Neolithic.[49] The necessary woodworking was certainly not more complex than building a LBK (Linear Pottery Culture) long house and domesticated cattle had also been known since the early Neolithic.[50]

Various authors see the necessary prerequisite for the diffusion of the wagon in a higher level of interconnectedness.[51] In comparison to the loose, relationally organized gift exchange circles of the 5th millennium BC, both more intensively communicating exchange circles and early forms of trade become established at different points in time during the first half of the 4th millennium.[52] Especially for the area between the western Black Sea region, the Alpine region and the Baltic Sea coast that is taken up by early wagons, it can be substantiated that communication gradually intensified in the period between 4000 and 3600 BC; far-reaching networks indeed emerge already in the 5th

48 Rogers 2003, 112–118.
49 Among others, see Lenneis 2013; Brandt 1967; Meier-Arendt 1975.
50 Benecke 1994a; Benecke 1994b; on the harness, cf.: Boroffka 2004.
51 Maran 2004b; Klimscha 2013; Burmeister 2011; Furholt 2009.
52 Klimscha 2011; Klimscha 2013 [2014].

millennium BC, but they are only able to transfer a few isolated prestigious objects.[53] In the first half of the 4th millennium, however, considerably denser networks that connect different culture groups in the northwestern Black Sea region, Poland and southern Scandinavia can be traced, for example on the basis of flint adzes.[54] This is the environment in which, we have to assume, the takeoff of the wagon in central Europe took place. Before the middle of the 4th millennium, new ideas, including the use of wheel and wagon, had the ideal environment to spread.

It is more difficult to evaluate a possible relative advantage of the wagon over other vehicles than to determine the manner of its spreading. Even if the evidence of earlier vehicles is very scarce in the archaeological material, we have to regard, after critical perusal, various other vehicles as near-simultaneous or simultaneous phenomena – which is also true for the evidence of harnesses. The picture becomes even more complex when the wagon technology is compared to other uses of animal traction: At the moment, the earliest datable depictions of sleighs in Asia Minor, Syria and Mesopotamia are simultaneous with those of early wheeled vehicles,[55] earlier evidence, which might even date to the 2nd century of the 4th millennium BC, is known in the Alpine region.[56] Simultaneously, travois appear in Europe,[57] and the first litters in Egypt can be dated to the late 4th millennium.[58] During the second half of the 4th millennium, there is an international fascination regarding the disembodiment of movement, be it by simple, animal-drawn machines or human-carried litters. At the same time, the use of animal traction is transregionally spread and leads in those regions where it is appropriate to use wagons to the adoption, local adaptation and production of wheeled vehicles.[59]

4.2 Critique of methodology

In contrast to traditional archaeological maps, the Digital Atlas improves the comparability of such mappings. So far, no mapping standards exist in the archaeological sciences. Now, the Digital Atlas of Innovations makes it possible to combine data from different sources and to make different entries comparable by harmonizing or replacing their scales and map bases. The heuristic potential of the maps can be better exploited due to the freely adjustable scales and time intervals. In contrast to fixed maps, it is possible to challenge the interpretation of a map by showing possibly more appropriate dating intervals, map sections and find combinations. In doing so, the maps become less of a suggestive illustration and more of a tool for one's own research and of a research object.

The dynamic user interface of the Digital Atlas allows the user to define freely chosen time intervals and to check them against each other. For example, if one also includes the wagons of the first half of the 3rd millennium, the sharp increase from 3500 BC onwards levels out considerably, showing clearly how much greater the number of finds becomes after 2500 BC. Such options allow not only to reassess the informative value of maps, but also to deduce new questions from the map and to pursue them on the basis of the same stock of sources and the same map basis (Fig. 9). By adding classified attributes, specific problems can be solved. Considering the chosen example, it becomes clear that the turn from the late 4th to the early 3rd millennium is also accompanied by

53 Klimscha 2013.

54 Klimscha 2007; Klimscha 2011.

55 Bernbeck 2004; Crowel 2004; Burmeister 2004a; Mischka 2011.

56 Harwath 2002.

57 Schlichterle 2002, 26–30.

58 Köpp 2008.

59 Cf. also the vessel with a yoke depiction from Tell el-Farah (North), Palestine (Dayagi-Mendels and Rozenberg 2010, 39 Fig. 4).

a change in the archaeological record: While the majority of finds in the 4th millennium comes from unknown circumstances of finding, the amount of settlement finds increases considerably in the first half of the 3rd millennium (Fig. 9). Without scientific methods, it was difficult or not possible to date early wagon finds by other methods than typological chains. Therefore, the non-datable wheels had to be derived from the datable ones and these had been found mainly in western Asia before the radiocarbon revolution.

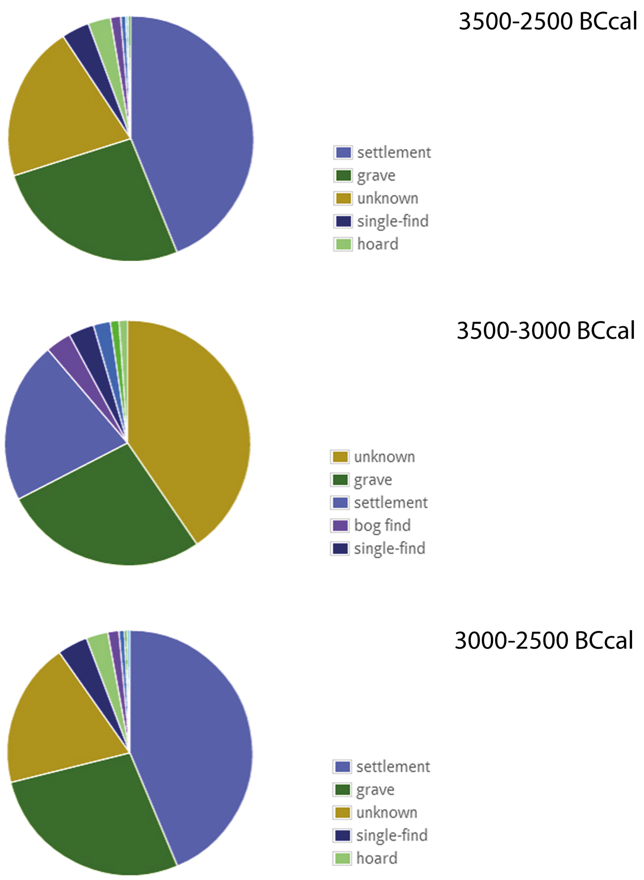

Fig. 9 | Comparison of the find contexts of wheeled vehicles in three time intervals. Indications of the use of wheeled vehicles between 3500–2500 BC, 3500–3000 BC and 3000–2500 BC. The special role of the interval 3500-3000 is prominent [find_type=Wheel & Wagon; added categories: Context_type; time intervals= -4700/-3000, -4700/-2500; n=409].

4.3 Technology and evidence of early wagons

A critical examination of the sources also shows that the problem is considerably more difficult because, already in this early period, significant technological differences between the individual finds of wheeled vehicles can be observed. There is evidence of both two- and four-wheeled wagons, both fixed and rotating axles, as well as one-, two- and three-piece disk wheels.[60] It can, however, be shown that there is a connection despite the local technical differences because the wagon is not restricted to one particular type of source in this time, but represented in regionally different ways: in the Hessian-Westphalian region

60 Cf. on this the comprehensive contributions in: Fansa and Burmeister 2004.

as pecked depictions on the wall stone slabs of the gallery graves of the Wartberg Culture,[61] in Flintbek as tracks under a burial mound (tumulus) of the late Funnelbeaker Culture,[62] in Poland as depictions on funnelbeaker pots[63] and as cast copper sculptures,[64] in the area of the Baden Culture as models,[65] in the northern Pontic region as grave goods,[66] in the lakeside settlements of the circum-Alpine region and the moors of northwestern Germany and the Netherlands as realia finds,[67] and, finally, in the Cucuteni-Trypillian Culture as animal figurine on wheels.[68] Two large-area find zones have to be mentioned that can be roughly separated by an imaginary line from the Alps to the Black Sea. In one zone, wagon models and pictures come mainly from settlements (and the art trade) (Fig. 10), in the other zone, full-size wagons and parts of wagons, which were probably actually used, predominantly come from graves, but also lakeside settlements and moors (Fig. 11). So we also have to take into account, besides the special conditions of survival, that a considerable cultural filter has caused the modern find distribution. This in turn poses the question whether maybe the lack of early wagons in western Asia is also caused by a lack of grave finds or the non-existing custom of wagons as grave goods.

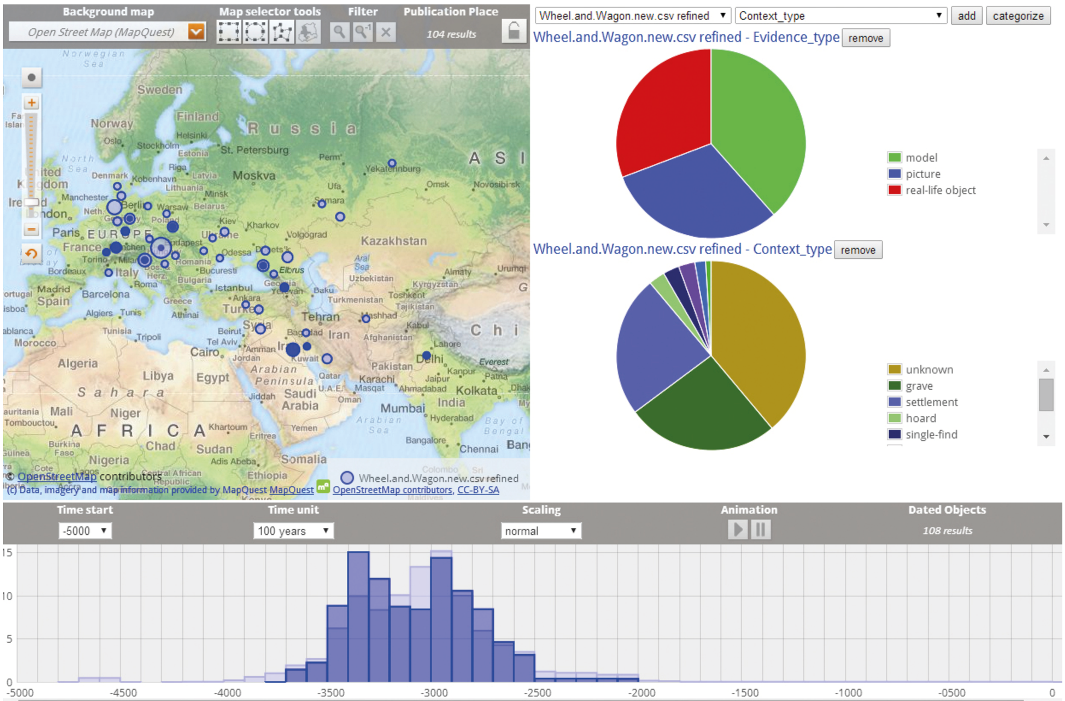

Fig. 10 | Definition of a time interval and its combination with an attribute field. The filled symbols show all indications of the use of wheeled vehicles between 5000 and 3000 BC found in a) settlements [find_type=Wheel & Wagon; added categories: Evidence_type, Context_type; time interval= -5000/-3000; n=108].

61 Günther 1990.
62 Zich 1992–1993.
63 Milisauskas and Janusz 1982.
64 Bakker 2004, 284 Abb. 2.
65 Maran 2004a.
66 Trifonov 2004.
67 Schlichterle 2004; Bakker 2004; Burmeister 2004a.
68 Gušev 1998.

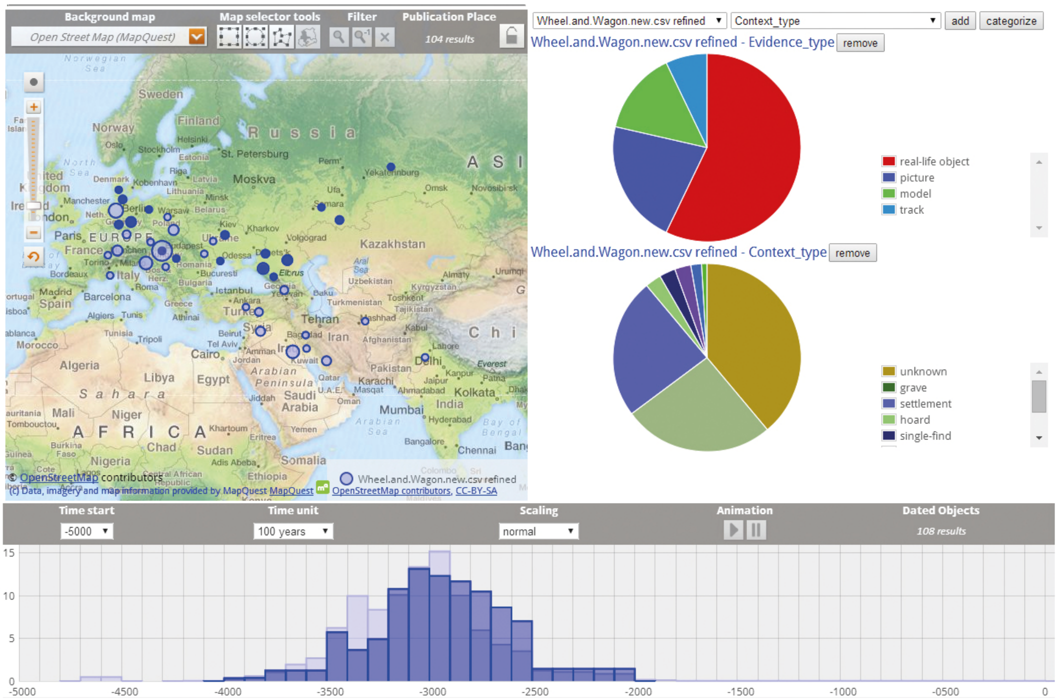

Fig. 11 | Definition of a time interval and its combination with an attribute field. The filled symbols show all indications of the use of wheeled vehicles between 5000 and 3000 BC found in graves [find_type=Wheel & Wagon; added categories: Evidence_type, Context_type; time interval= -5000/-3000; n=108].

Fig. 12 | Distribution of four-wheeled vehicles in the 4th millennium BC [find_type=Wheel & Wagon; added categories: Context type, Evidence_type, Wheel_number; time interval= -5000/-3000; n=108].

St. Burmeister has pointed out that the different technologies suggest that the idea, not the artifact was transferred.[69] Different communication networks, however, can be better outlined already. The mapping of four-wheeled wagons in the 4th millennium makes this clear (Fig. 12): They are restricted to Poland, the Carpathian Basin, the Caucasus and Syria-Mesopotamia. It could be argued that almost three quarters of the evidence of wheeled vehicles is undetermined and that the finds from lakeside settlements and moors are parts of wagons whose number of wheels cannot be reconstructed anymore. Even if there is a high potential for error, it can be held against this that at least the pictorial sources are distributed over the entire area. Therefore, one is indeed allowed to assume that the wagon of western central Europe might actually have been just a light two-wheeled cart because such carts are the only wagons that we find in the Wartberg Culture, and, furthermore, two-wheeled wagons with an A-shaped chassis, developed from the travois, are known from the western Alpine region.[70]

5 The spread of early scales

Weighing has permanently influenced the development of early civilizations like hardly any other technology. Using scales and weights, things could be compared in a new way. Metals, measured according to their weight, could thus become an equivalent for value and trade goods *par excellence*. Where goods were traded for goods, this increasingly happened on the basis of the equivalence with precious metals. Weighing became a prerequisite for a new way of valuation that considerably simplified exchange and in effect transformed the Bronze Age world.

Despite its obviously great importance for the development of protohistoric economies, the development of the cultural technique of weighing has been only inadequately examined so far. Not even such fundamental questions like the origin of weighing have been answered unanimously. Furthermore, existing studies are usually characterized by a restricted focus both in diachronic and synchronous respects. Given the multitude of cultures across which the weighing spreads in the Bronze Age and their wide spatial and temporal dimensions, the examination of the emergence and spread of scales and weights and the resulting cultural consequences demands new methods and approaches like the ones offered by the *Atlas of Innovations*.

Some first results of a study on the development of weighing in Egypt in the 3rd and 2nd millennium will be outlined and their implications for future research up to a more global history of weighing in early civilizations will be discussed.[71]

When considering weighing, the instrumental medium, namely the measuring instruments, can be distinguished from the measure; this is true for any other measuring technique, too. Furthermore, looking at the measure, one has to differentiate between abstract measuring systems and their physical materializations. We encounter the first measuring systems in the sense of establishing certain standard measures and their interrelationships when administrative writing developed in the second half of the 4th millennium in the late Uruk period.[72] First of all, it has to be noted that a history of weighing always has to address two aspects of the same technology, aspects whose development and spread are influenced by fundamentally different factors. For instance, the existence of certain manual skills and craftsmen's knowledge are decisive for the production and spread of scales. The possibility to establish and maintain measurement systems is subject to completely

69 Burmeister 2004b.

70 Pétrequin et al. 2002, 62, fig. 9.

71 The results of this study which was conducted jointly by David Allan Warburton and Jochen Büttner will soon be published under the title "Egypt in the History of the Balance".

72 Nissen, Damerow, and Englund 1993.

different conditions, for example the societal conditions under which social norms can be established and controlled. At the same time, both aspects are inseparable. Scales without weights and weights without scales do hardly make sense; the relationship between the abstract measurement system and the physically existing weights can only be established and controlled on the basis of the scale.

When comparing weighing to the earlier developed techniques of length and volume measurement, one issue emerges that is of great importance for a comprehensive history of the development of weighing. Each elongated object, for example a simple stick, can be used for measuring length, each vessel, for example a drinking bowl, can be used for measuring volume. Thus, the respective measuring instruments have historically seen existed long before the first measuring systems, in the case of length measurement universally, in the case of volume measurement culturally. Furthermore, stick and bowl embody their own physical, natural measures. One can measure the same length elsewhere; one can drink the same amount as now at another time. The application of such natural measures is initially restricted to a certain spatial and temporal context. How abstract measurement systems could have developed from such genuine acts of measuring can be easily imagined and a reflection of natural measures in early measurement and counting systems has actually been already stated.

The assumption that a similar mechanism can be used to explain the origin of weighing is confronted with the observation that the earliest scales are already highly specialized instruments which were obviously produced especially for the purpose of weighing. Moreover, these instruments do not represent a measure; they already seem to imply the existence of weights as material representatives of a weight system. Besides the search for the earliest scales and weights, one has, therefore, to consider, with regards to the question of the origin of weighing, possible precursor technologies and acts from which weighing could have developed.

On the instruments' side, one can, for example, make out the carrying pole as a possible precursor of the scale, a precursor with which first experiences regarding the balanced equilibrium were had. Concerning the measurements, weight stones are known, at least from later times. These weight stones do not fit into one of the measurement systems valid at the respective time. They have to be, as is often proven by an inscription, rather understood as evidence of real transactions (*this* rope weighed as much as *this* stone) which become, in this way, comprehensible and repeatable. Whether such weight stones were used for simple weighing operations even before the existence of weight systems, for example for the purpose of rationing (the division of one good into even parts according to weight) is an unsolved problem. Some pieces of evidence actually suggest that the rationing of wool, which is difficult to measure according to volume, could have played a decisive role in the development of both the scale and the weights.

Many pieces of evidence indicate that one has to search for the origin of weighing, at least in the modern sense, in Egypt. Three independent observations support this assessment, the localization of the earliest object which can be classified as a weight and dated with relative certainty; the localization of the, according to present knowledge, earliest surviving scale and an argument *ex silentio*. Several pieces of evidence could suggest that weighing had its origin in Mesopotamia. The earliest scales and weights recorded there, however, are considerably later, namely from the second half of the 3rd millennium.[73] In addition, none of the numerous measurement and counting systems documented in archaic texts could be identified as a weight system. With great certainty, weighing was

73 The earliest surviving set of weights from a well-dated context comes from the Royal Palace G of Ebla (*c.* 2400–2300 BC) in North Inner Syria, the earliest royal weight with an inscription from Mesopotamia has to be dated to the reign of Uruinimgina of Lagash (*c.* 2400 BC). Peyronel 2012 and Peyronel and Ascalone 2006.

therefore not part of the administrative activities which in turn can be taken as significant evidence that the technique of weighing was not present in the Uruk period.

The identification of objects as weights is fraught with difficulties. For example, the existence of several objects with the same weight in one find context cannot be taken as evidence for the existence of a weight system or as evidence for the existence of scales because equality in weight can also be the contingent result of a division according to equal volume, for example. Even the fact that one object fits, according to its weight, into a weight system attested for later times is of little significance since, among a large number of objects, always such objects will be found, too, whose weight will correspond, within a certain accuracy, to a randomly given weight. L. Rahmstorf has presented a series of criteria that should be applied when answering the question whether or not a given object is a weight.[74] When one applies these criteria, an Egyptian quartzite on which the name of king Narmer is inscribed has to be regarded, according to present knowledge, as the earliest weight that can be dated with certainty. The spelling of the name is typical of the time. Thus, the weight should date to the reign of Narmer around 3000 BC (Fig. 13).

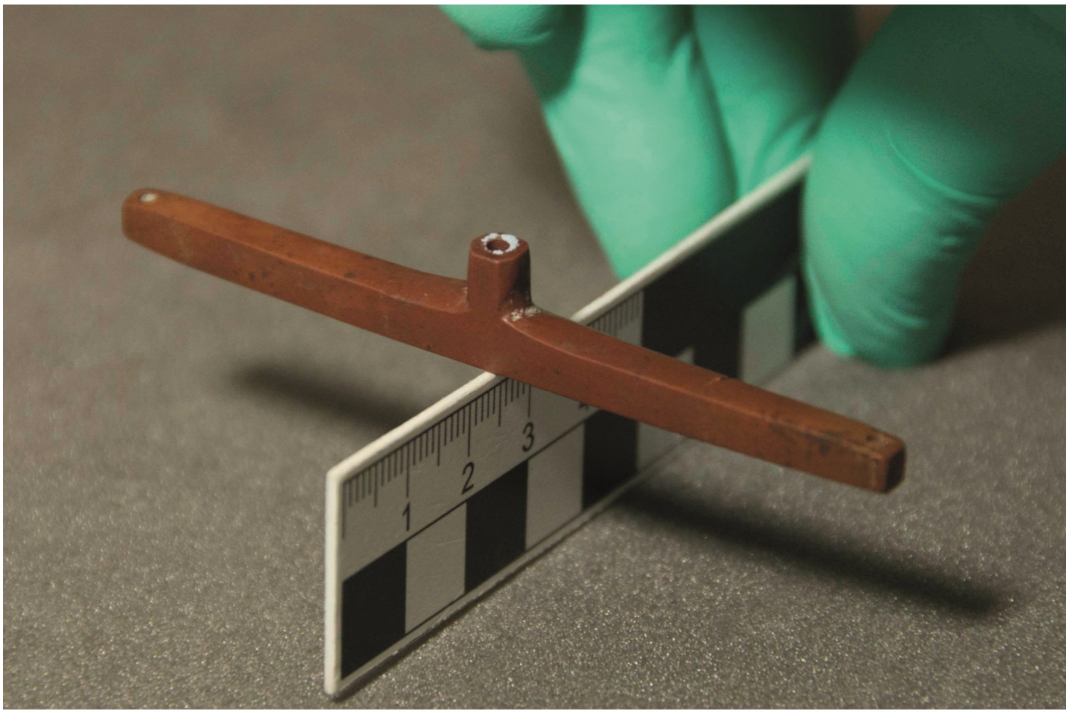

Fig. 13 | Scale from Egypt, probably dating to the late 4th or early 3rd millennium.

The earliest scales have so far received far less attention than the weights. A small (8.7 cm) scale made of brown limestone, today part of the permanent collection of the Petrie Museum in London, has often been classified in literature as the earliest surviving scale. Some authors have put this scale into the 5th millennium, a dating that has continued to haunt popular scientific accounts of the history of weighing to the present day. There is, however, no reason for such a dating; on the contrary, in the prehistoric cultures of Merimde, Omari and Badari, any kind of evidence of weighing systems is missing – even for simplified ones. The scale was acquired by Flinders Petrie who only made a comment

74 Rahmstorf 2006.

to the effect[75] that the piece was made "of pink-brown limestone, a material often used in Prehistoric Egypt but seldom later."[76]

Petrie's notes give rise to the assumption that the scale comes from Upper Egypt, possibly from the region between Abydos and Naqada where large cemeteries of the Predynastic and Early Dynastic periods can be found.[77] Especially the missing evidence of writing and administrative structures, i.e. the context in which we assume the development of weighing systems, argues against a Predynastic dating.[78] Where exactly the scale came from will probably remain unknown. When one supposes that it belonged, as a burial object, to an Early Dynastic tomb, the localization in Upper Egypt, in a time before the main cemeteries of the elite were relocated to Memphis, is plausible.

That the object is indeed a scale becomes clear when looking at an illustration from the tomb of Hesyre, a high official of the Third Dynasty (*c.* 2650 BC). In the tomb, several chests are illustrated that contain the tools and instruments of experts. Among other things, two chests with two scales each and the associated sets of weights are depicted. The scales in this depiction are identical with Petrie's scale, supporting its dating to the Early Dynastic period.[79]

The indications of the existence of scales and weights at around *c.* 3000 BC in Egypt and the lack of evidence from other civilizations for this time have to be taken, for the time being, as strong evidence that weighing originated in Egypt. Independent of the question about the origin, one has to note that weighing spread quite rapidly. As early as 2600 BC, scales and weights can be traced from the Aegean to the Indus Valley Civilization.[80] A more detailed understanding of this diffusion both as a consequence and a visible piece of evidence of cultural contacts remains a desideratum of future research (Fig. 14).

Weight-metrological research, which can look back on a comparatively long tradition, has presented material on the emergence, spread and development of weights and weight systems in the respective cultures. With a few exceptions, however, it has hardly been attempted so far to integrate this information into a more global picture of the spread of weight and weight systems. Using the Digital Atlas as a tool, we want to achieve this integration. On the other hand, only scattered data on scales and their spread has been presented so far.[81] In order to close this research gap, a team of experts on the respective cultures has been formed who systematically collect the archaeological sources on scales. Once this has been done, they will be able to map the spread of scales and, finally, to relate it to the spread of weights and weight systems. That the rapid spread and development of weighing has to be understood in connection with its being embedded into economic contexts, especially exchange relationships, has frequently been acknowledged. Rahmstorf, for example, writes:

The practice of weighing seems to have been common from around 2500 BC onwards. It is not by chance that around this time all the most important skills in working with

75 Petrie 1920, 29.

76 Petrie 1920.

77 Stephen Quirke established these inferences from Petrie's papers (pers. comm. 2013).

78 Permanent concentrations of power in Egypt can only be verified from 3600 BC onwards. Towards the end of the 4th millennium, various scholars assume a complex bureaucracy that controlled the transfer of goods and can be verified, for example, in Abydos Umm el-Qaab. Cf. Klimscha 2013 [2014] with further literature.

79 A small balance beam from Tell Fadous-Kfarabida, Lebanon, may date to the early 3rd millennium. Genz 2011.

80 Rahmstorf 2006, in particular fig. 6.

81 The history of the discussions of the Egyptian balance has been summarized (with references) by Jenemann 1988; and in Kochsiek & Gläser 2000, 120–126; and Robens 1989. For the history of weighing in the Aegean, see, in particular, Michailidou 2010; in the Indus Valley Civilization, see Keynoyer 2010; in Mesopotamia, see Alberti, Ascalone, and Peyronel 2006; and in central Europe, see Rahmstorf and Pare 2007.

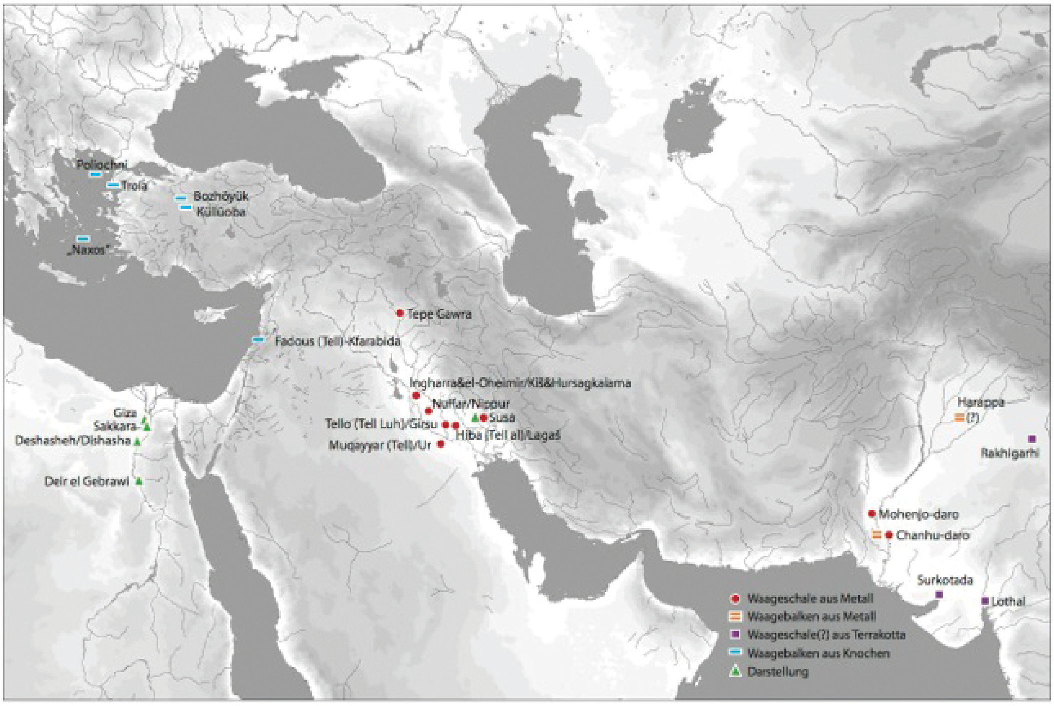

Fig. 14 | Distribution of early scales in the late 4th and the 3rd millennium (according to Rahmstorf 2012b).

gold were known in Mesopotamia and the eastern Mediterranean. A clear affinity between complex metalworking and weighing practices is evident. With the widespread trade and usage of precious metals like gold, silver and tin not only the manufacture of these materials reached new levels, but the metals themselves had become standards of value which could be measured exactly by their mass.[82]

The economic exchange relationships of the 3rd millennium root in a long tradition of exchange circles that bartered, for example, obsidian and prestigious objects, and in some cases had done so since Neolithic times. With the rise of permanent concentrations of power in Egypt and Mesopotamia and the wide availability of different transport technologies in the eastern Mediterranean, however, a marked circulation of goods can be observed.[83] The scale technology becomes available in an intensively communicating world that documents and controls its exchange relationships with the help of early bureaucracies. The structures of the centrally administered city states belong among the conditions that made the implementation and guarantee of weighing standards possible. At the same time, weighing fundamentally changed the economic exchange relationships when the concept of the weight of precious metals as an indicator of value developed. The *Digital Atlas of Innovations* is designed to enable a deeper understanding of this correlation by mapping, besides the spread of the technique of weighing, also other indicators of the changing economic conditions so that their historical developments can be interrelated.

Only comparatively few scales and scale fragments have survived from these early times until the end of the New Kingdom at around 1000 BC. There is, however, a tradition of depicting scales which dates back to the Old Kingdom so that a continuous series of depictions, if not necessarily many, from the respective period has survived. In the New Kingdom, scale depictions can primarily be found as part of a scene from the judgment

82 Rahmstorf and Pare 2007, 38.
83 Klimscha 2013 [2014].

of the dead in which soul of the deceased has to undergo the 'Weighing of the Heart.' This scene has been repeatedly depicted in tombs, on sarcophagi and in papyri. To this, written sources can be added in which scales and weighing are mentioned and described, like "The tale of the eloquent peasant."[84] By looking at the overall picture for the first time and analyzing all available sources, it could be shown that the upright balance scale depicted in the New Kingdom is a highly function-optimized instrument. Surprisingly, its development can be tracked without gaps over a period of 1500 years on the basis of surviving depictions, written sources and artifacts (Fig. 15). Thus, it has been shown, for example, that the indicator device of these scales with which the horizontal position of the beam in balanced equilibrium was controlled has developed in a process that can be called, with reference to biology, preadaptation, namely the gradual modification of an existing structure for a new function.

Fig. 15 | Depiction of an Egyptian scale.

The earliest depicted scales are hand-held, equal-armed beam balances with a long beam perpendicular to the weighing beam; at the upper end of this vertical beam, the scale is held. A scale with a resolution substantially greater than the smallest weight unit of the used weight system (at the time probably the gold *deben* of *c.* 13.5 g), i.e. a scale that shows very large amplitudes when the difference in weight between the goods which are to be weighed and the used standard weights is roughly equal to the smallest weight unit, is useless in everyday life since no equilibrium can be achieved. Because of the heavy vertical beam with its extended bottom end, the center of gravity of early Egyptian scales is positioned low in relation to its pivot point. These scales heavily tend to return to their horizontal equilibrium, their resolution is low. As has been confirmed by model calcu-

84 The origins of the text probably take us back to somewhere around 2000–1900 BC. The copies of the tale's text that are preserved today probably date to the end of the Twelfth Dynasty (Parkinson 1991: xxv–xxviii), *c.* 1800 BC.

lations, the function of the vertical beam is to adjust the scale to the weighing accuracy demanded in everyday life.

Over time, the requirements regarding the weighing accuracy and the resolution of scales rose. One of the mechanisms with which the scales' accuracy was increased was the addition of a plummet. With the aid of the plummet, the horizontal equilibrium of the weighing beam could be controlled better. The already existing vertical beam was used as a vertical reference for the plummet – probably for this purpose, a center line was carved into the beam –, thus assuming a second function besides the adjustment of the weighing accuracy.

With the development of the upright balance scale of the New Kingdom, which is then not hand-held anymore but attached to a stand, the technological development of the Egyptian scale reached its peak. The calculated reconstruction of such upright balance scales has shown that they were actually very accurate. The heavy vertical beam of the early scales that made the scale 'less accurate' had lost its justification. It had, however, not completely vanished, but had mutated into a light triangular pointer which continued to allow the control of the horizontal position of the weighing beam by interacting with the plummet. Thus, an existing structure was gradually modified for a new function while losing the original function – preadaptation.

The design of other functional components of these scales, like the form of the weighing beam and the attachment of the weighing pans' suspension at the end of the weighing beam, have also been chosen in such a way that this exact choice can be identified, from a present-day perspective, as improving the scales' accuracy. For example, the long weighing beam is thicker in the middle, thus increasing the weighing accuracy without reducing the stability requirements too much. A combination of two other details, the weighing pans' suspensions emerging horizontally at both ends of the weighing beam and the beam ends being designed in the shape of a lotus flower, ensures that the leverage ratios do not change (or only imperceptibly) when the scale is dislocated, which also improves weighing accuracy. The design of the individual components of these scales seems to solve, from a present-day perspective, subproblems that emerged when such scales were built. A first survey shows that many of these design features can also be found on scales from other regions and times. Since the design of the respective components represents indeed optimized solutions, but by no means solutions without any alternative, one probably has to assume that such solutions did not usually develop independently, but spread once they had been established. The means of the *Digital Atlas of Innovations* are intended to help better understand the development and spread of such subproblems as part of a complex innovation process.

6 The beginning and spread of metallurgy

Metallurgy is one of the key technologies of the Copper Age innovation package. The complex technology of casting copper demands specialized knowledge, and the use of metal as a raw material opens up new technical possibilities which, in turn, allow innovations in other areas. Childe identified smiths as the first full-time specialists in history who also had, as itinerant craftsmen, played a leading role in the rapid and far-reaching spread of knowledge from Mesopotamia to Europe.[85] In reply to the model of a single origin in southwest Asia, the model of multiple regions of origins has been offered since the 1960s.[86] As is the case for numerous other innovations, this question cannot be answered conclusively, but with a higher data density and chronological specifications, the

85 Childe 1950, 7–8.
86 Renfrew 1970; opposing this: Pernicka, Rehren, and Schmitt-Strecker 1998.

mappings show one extensive and continuous geographical zone of metallurgical activity in the vicinity of copper, gold and lead deposits in the mountain regions of southwest Asia.[87]

6.1 State of sources and data stock on the early metallurgy in southwest Asia

Studies on early metallurgy in southwest Asia draw upon different types of sources that come from different points of the *chaîne opératoire*: Archaeo-metallurgical and mining-archaeological research in prehistoric mining districts and in production centers give some indication of the knowledge associated with the extraction and processing of metals and the organization of this production. In the last decades, selected mining districts have systematically been examined: one focus of research was on the southern Levant where copper had been systematically extracted in the Arabah wadi since the 4th millennium BC.[88] Another focus was on Anatolia where extensive surveys have recorded prehistoric mining districts in eastern Anatolia[89] and excavations have taken place in the mines of Kestel and Götepe in southern Anatolia.[90] Among the numerous Iranian deposits, especially Talmessi,[91] known as silver mine in Sasanian times, and the mining district around Veshnoveh,[92] which had been in use since the 3rd millennium BC, have to be mentioned. More recently, systematic studies on the copper and gold deposits in the Caucasus have begun.[93]

Ideally, the analysis of metal artifacts enables findings on the origin of the raw material and the production technique. Objects are mostly found in special survival situations, for example as grave goods or in hoards. Given these particular circumstances of discovery, the majority of analyzed metal objects is not concentrated near the mineral deposits, but in the large cemeteries of the Mesopotamian lowlands and in elite burials in the mountain regions. In total, several thousand analyses of metal artifacts from the southwest Asian area are available.[94]

On the basis of such heterogeneous data, a history of metallurgy can yet be painted only with a broad brushstroke. It began with the use of native copper and silver for jewelry objects in the early Neolithic societies of southwest Asia and was followed by a period in which small tools were made of native copper by cold and warm forging. Cast copper artifacts appeared almost simultaneously in the second half of the 5th millennium BC in southeast Europe[95] as well as in western and southern Asia.[96] The mastery of casting opened up new possibilities of mixing metals, and different copper alloys can be detected that had been systematically produced since the late 5th millennium BC. Arsenic bronze is the most important one of these alloys: the addition of arsenic to copper makes the metal harder and produces a silvery color. The alloying of arsenic, which is volatile at high temperatures, and copper was accomplished by a multi-level process in which an iron-arsenic speiss was produced in a separate process and later smelted together with the

87 Roberts, Thornton, and Pigott 2009.
88 Summary in: Hauptmann 2006.
89 Wagner and Öztunali 2000; cf. also Yalçın 2003.
90 Synthese: Yener 2000.
91 Pernicka, Momenzadeh, et al. 2011.
92 Stöllner et al. 2011.
93 Summary on the state of research in: Courcier 2014.
94 Hauptmann and Pernicka 2009; Stech 1999.
95 E.g. in the cemetery of Varna, cf. Hansen 2013: 39–40.
96 E.g. leopard weight from Shahi Tump, Pakistan, cf. Mille, Bourgarit, and Besenval 2005; hoard from Nahal Mishmar, Israel; on the dating cf. Klimscha 2013, 36–37.

copper. This method has been verified for the late 4th millennium BC in the metalworkers' settlement of Arisman in western central Iran;[97] probably, such a method was also used in Tappe Hesar at the northern edge of the central desert.[98]

Arsenic copper has been found throughout southwest Asia where it had been used since the late 5th millennium BC, so the knowledge of the method and the formula spread rapidly. Triple alloys of copper, arsenic and antimony are rare, for them, regions of origin can be located in the Caucasus and the Levant, for example.

Since the 4th millennium BC, cupellation has been known in the production centers in central Asia, Iran and Anatolia, a method that made the extraction of silver from silver-lead ores possible.[99] Small cast or hammered silver objects have been found especially in elite contexts since the 4th millennium BC. The combination with copper results in a silver-copper alloy which shimmers like silver and is very rare: we know an arrowhead from the Riemchen Building in Uruk[100] and another from the simultaneous Arslantepe VIA;[101] in the meantime, further finds from a slightly later elite burial in Arslantepe VIB1[102] can be added to this list. Lead was also used as an alloying material; especially three-dimensional objects like cylinder seals which were complicated to cast were made of lead-copper. Admittedly, the addition of lead did not improve the casting properties to any degree,[103] yet the material was regularly employed for certain artifact groups. The best-known copper alloy, tin bronze, was used regularly only from the second half of the 3rd millennium onwards, but not in all regions of southwest Asia to the same degree: the elite burials in the early Dynastic cemeteries show a high amount of tin bronzes, the Iranian highlands, however, did not participate in this new technology until well into the 2nd millennium BC.[104]

6.2 The spread of metallurgical innovations

The almost simultaneous appearance of cast copper objects in the 5th millennium BC and of silver cupellation in the 4th millennium BC suggests a rapid spread of the associated knowledge over large distances in the existing social networks. In contrast, the silver-copper projectile point from Uruk could have been transferred as a single object, particularly since all similar finds are concentrated in Arslantepe.

The reasons for the search for innovations in metallurgy were not (only) practical ones: the early artifacts made of metal have a function as a symbol in social relationships; besides, color and esthetic quality were certainly important factors in their spreading.[105] Esthetic issues also seem to have played a role when adapting alloy formulas so that one even accepted a deterioration of technical properties, for example in the case of lead-copper. Finally, the non-adaptation of innovations from one region in another suggests, like the absence of tin bronze in Iran, decision processes that are rooted in the political and economic history of the respective regions.

Even if the trends summarized here are, in principle, valid for the early metallurgy of southwest Asia, numerous regional differences become apparent at the same time on

97 Rehren, Boscher, and Pernicka 2012.
98 Thornton, Rehren, and Pigott 2009.
99 Hess et al. 1998; Pernicka, Rehren, and Schmitt-Strecker 1998; Pernicka 2004; Pernicka, Momenzadeh, et al. 2011.
100 Pedde 1992, no. 974.
101 Frangipane 1985.
102 Hauptmann and Palmieri 2000, 77–79; Frangipane et al. 2001, 130.
103 Mille, Piccardo, et al. 2011.
104 Helwing 2009; Helwing 2013.
105 Roberts, Thornton, and Pigott 2009.

closer examination. This uneven development in the individual regions only becomes visible due to the increased data basis and the thus increased comparability. Their localization in time and space allows by now the examination of local phenomena in global developments and, therefore, the revision of general models.[106] In this area, the Atlas will become an important tool for further studies.

7 Outlook

The *Digital Atlas of Innovations* is the contemporary method to make the development and spread of technologies visible. After it has just become possible, due to the radiocarbon revolution about 30 years ago, to understand the actual temporal dimensions of the development of human culture, the research into technologies and their social prerequisites and consequences has also become possible for the first time. Many things are still in the early stages, but the research into the development of technology is a key to understanding history.

106 E.g. Thornton and Roberts 2009.

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