MACHINES, POWER AND THE ANCIENT ECONOMY*

By ANDREW WILSON

(Plates I–IV)

This paper explores, in a very preliminary fashion, the relationship in the ancient world between the design and use of mechanical technology, social or political patronage and investment, and economic return, using three main areas as case studies: water-lifting devices, the water-powered grain mill, and the diverse uses of water-power in mining. The emphasis is on the use of devices and techniques which replaced human power with alternative power sources, and especially on water-power for driving machinery and hydraulic mining techniques employing the erosive power of water. It is argued that water-power was used on a wide scale and in diversified forms at an early date (by the first century A.D.), and that the use of mechanical technology to perform economically critical work had an important impact on economic performance and the potential for *per capita* growth, especially in the latter centuries B.C. and the first two centuries A.D. Conversely, in the third century A.D. the cessation of the employment of hydraulic mining techniques enabling large-scale extraction of gold and other metals may have had an adverse economic impact on the economy as a whole. Growth and progress do not necessarily follow a linear pattern of advance; technologies are lost as well as adopted.

HISTORIES OF ANCIENT TECHNOLOGY

The study of ancient technology has generally been somewhat sidelined from mainstream ancient history; ancient technology is something to be admired when we encounter a structure like the Pont du Gard or the Colosseum, but it is not often considered as a major explanatory factor in historical processes of the Greek or Roman period. This is in striking contrast to the emphasis placed by medieval historians on technology as an agent of social change. The reasons for this neglect are several, and not least are the deterrents of having to read highly technical Greek by the likes of Hero of Alexandria, or the confusing and often corrupt Latin of Frontinus, Vitruvius, and other technical writers; or the difficulties of studying the usually poorly preserved and often frankly bewildering archaeological remains of mechanical installations. Even where technical writers are studied, the social and economic implications of their texts are often little explored. The situation was not helped by the fact that the 1950s *Oxford History of Technology* explicitly refused to consider the socio-economic impact of the technologies it described,[1] for which it was rightly and roundly castigated by Sir Moses Finley.[2] Although Finley's later article, in the *Economic History Review* of 1965, on 'Technical innovation and economic progress in the ancient world', did attempt to fit

* This article has benefited greatly from discussions with friends and colleagues, none of whom is to be held responsible for the views expressed here. Lisa Fentress provided hospitality in Rome and Tuscany during which much of this article gestated; and Örjan Wikander, Philippe Leveau, Kevin Greene, Bruce Hitchner, Claude Domergue and Jacques Seigne kindly supplied offprints or previews of forthcoming work. Earlier versions of this research were presented to the Triennial Conference of the Classical Association in Oxford in July 2001, and to the Oxford Classical Archaeology Seminar in November 2001, and I thank the audiences on both occasions for comments. I also owe a debt of gratitude to the Journal's anonymous referees, one of whom in particular forced me considerably to improve the argument; I, of course, remain responsible for the resulting imperfections. Finally, I should like to thank Helena Tomas for information on the production figures for her grandmother's water-mill in Livno, Bosnia.

[1] C. Singer, E. J. Holmyard, A. R. Hall and T. L. Williams (eds), *A History of Technology* vol. 2. *The Mediterranean Civilizations and the Middle Ages c. 700 B.C. to c. A.D. 1500* (1956), vi.

[2] M. I. Finley, 'Technology in the ancient world', *Economic History Review* (2nd ser.) 12 (1959), 120–5.

technology into its social context, it in turn effectively discouraged much further research by declaring that there was little of either technological innovation or economic progress, and the subject was therefore deemed unimportant.[3] His picture in fact reflects views developed largely by historians of medieval technology — Marc Bloch, Bertrand Gille, and L. T. White — who were at pains to stress that the Middle Ages were a time of technological innovation and progress unparalleled in any previous period of history.[4] It therefore suited their agenda to play down the achievements of the Classical world. Their analysis of the relationships between technological progress and social change was far in advance of the work of the few classicists who bothered to occupy themselves with ancient technology, and so it is hardly surprising that their more sophisticated models were rapidly adopted.

Although thinking on the ancient economy has moved on considerably since then, the general histories of ancient technology currently available are some twenty years old and still subscribe in some form to the broad outlook that the Classical world can take credit for relatively few new inventions; and that a number of social factors combined to retard innovation and inhibit the uptake and spread of new inventions.[5] On this view, ancient technology is seen as stagnant and underdeveloped, retarded by the widespread use of slave labour, and by lack of sponsorship for inventors and capital investment for new developments. This is held to be illustrated by the slow diffusion of the water-mill, supposedly invented in the second or first century B.C., but not employed on any significant scale until the fifth century A.D. It has been argued that the slow uptake of the water-mill was due to the retarding factors just described, and that it was only with the breakdown of the Roman Empire, the abolition of slavery, and the triumph of Christianity over an animistic conception of nature which removed inhibitions about the exploitation of natural forces[6] that social conditions became ripe for the spread of the water-mill. Following this, in the early Middle Ages water-power started to be applied to other tasks than simply the grinding of grain — to driving bellows, fulling mills, forge hammers, saws — a diversification of powered machinery that the ancient world had never known, which in turn enabled an economic revolution. The importance of the use of water-power to the debate lies, of course, in the fact that it represents the first real attempt to harness natural forces to do mechanical work.

Over the last twenty years there has been considerable progress in particular fields of the subject, notably in the history of water-power, and of water-lifting devices. A series of studies by Örjan Wikander has completely revised our picture of the use of

[3] M. I. Finley, 'Technical innovation and economic progress in the ancient world', *Economic History Review* (2nd ser.) 18 (1965), 29–45.

[4] M. Bloch, 'Avènement et conquête du moulin à eau', *Annales d'histoire économique et sociale* 36 (1935), 538–63; B. Gille, 'Le moulin à eau. Une révolution technique médiévale', *Techniques et Civilisations* 3 (1954), 1–15; L. T. White, 'Technology and invention in the Middle Ages', *Speculum* 15 (1940), 141–59; L. T. White, *Medieval Technology and Social Change* (1962); L. T. White, *Medieval Religion and Technology, Collected Essays* (1978).

[5] e.g. J. G. Landels, *Engineering in the Ancient World* (1978); D. Hill, *A History of Engineering in Classical and Medieval Times* (1984). The best general survey, though in need of updating, remains K. D. White's *Greek and Roman Technology* (1984), which raises doubts about primitivist views. See also G. W. Houston, 'The state of the art: current work in the technology of ancient Rome', *The Classical Journal* 85 (1989), 63–80, which stresses the importance of technology and shows how few works apply it to other questions.

[6] The view that animist conceptions of nature inhibited technological progress was still being defended in J. P. Oleson, *Greek and Roman Mechanical Water-lifting Devices: the History of a Technology* (1984), 403. However, Antipater's poem on the water-mill (*Anthologia Graeca* IX.418), where nymphs are said to be leaping onto the water-wheel at Demeter's command, shows that animistic beliefs need entail no such inhibitions.

water-power in antiquity.[7] The standard view is shown to be a prisoner of the biases in our evidence; there are few literary references to water-mills before the fifth century simply because ancient literary genres rarely talk about the banal objects of everyday life. With the rise of new genres of documentary evidence in the early Middle Ages — law codes, monastic charters, hagiography — the quantity of surviving evidence increases. In the last two decades, archaeology has been discovering more and more water-mills of Roman date. In 1997, Michael Lewis published a book entitled *Millstone and Hammer: the Origins of Water-Power*, in which he argued that the water-mill was invented not in the first or second century B.C., but in the third century B.C.; and that the diversification of water-power to tasks such as driving trip-hammers for crushing ore and pounding grain had already occurred by the first century A.D. As the supposedly slow uptake of the water-mill in antiquity was a prime example cited by the primitivists to illustrate the failure of ancient technology to achieve any significant progress, the demonstration that this position is false has wider repercussions for views of technology in general. Kevin Greene in particular has published a series of syntheses arguing for a much greater degree of technological development in antiquity; the most recent is a point-by-point refutation of Finley's 1965 article.[8]

Specialist research on particular branches of technology such as these takes a while to filter through into the consciousness of mainstream history; these revisions to our understanding of technological progress have not yet been applied to any significant degree to the study of the ancient economy, and the 'stagnationist view' has recently been defended in an article on the scope for economic growth in antiquity.[9] But, coupled with more general revision of thinking on ancient technology and with studies on the ancient economy which reject or radically modify earlier primitivist models to do with trade and both agricultural and non-agricultural production, these recent studies seem to demand a complete reassessment of the role of technology in the ancient economy. The purpose of this paper is to start from the newer thinking on ancient technology, especially the use of water-power, and to assess some of the implications for the study of the ancient economy, and of Roman attitudes to production and investment.[10] First, though, a word is needed on ancient attitudes to technology and the concept of *banausis*, the ancient disparaging of applied science.

[7] Ö. Wikander, 'Water-mills in ancient Rome', *Opuscula romana* 12 (1979), 13–36; *Vattenmöllor och möllare i det romerska riket* (1980); 'The use of water-power in classical antiquity', *Opuscula romana* 13 (1981), 91–104; *Exploitation of Water-power or Technological Stagnation? A Reappraisal of the Productive Forces in the Roman Empire* (1984); 'Archaeological evidence for early water-mills — an interim report', *History of Technology* 10 (1985), 151–79; 'Mill-channels, weirs and ponds. The environment of ancient water-mills', *Opuscula romana* 15 (1985), 149–54; 'Ausonius' saw-mills — once more', *Opuscula romana* 17 (1989), 185–90; 'Water-power and technical progress in Classical Antiquity', in *Ancient Technology. Symposium held by the Finnish Institute at Athens, 30.3–4.4 1987* (1990), 68–84; 'Water mills and aqueducts', in A. T. Hodge (ed.), *Future Currents in Aqueduct Studies* (1991), 141–8; 'Water-mills in Europe: their early frequence and diffusion', in *Medieval Europe 1992. Pre-printed Papers* vol. 3 (1992), 9–14; review of D. Castella *et al.*, *Le moulin hydraulique gallo-romaine d'Avenches "En Chaplix"* (Aventicum VI) (1994), *Opuscula romana* 21 (1996), 131–3; 'The water-mill', in Ö. Wikander (ed.), *Handbook of Ancient Water Technology* (2000), 371–400.

[8] K. Greene, *The Archaeology of the Roman Economy* (1986); 'Perspectives on Roman technology', *Oxford Journal of Archaeology* 9.1 (July 1990), 209–19; 'How was technology transferred in the Western provinces?', in M. Wood and F. Queiroga (eds), *Current Research on the Romanization of the Western Provinces* (1992), 101–5; 'Technology and innovation in context: the Roman background to mediaeval and later developments', *Journal of Roman Archaeology* 7 (1994), 22–33; 'Reflections on «Le temps de l'innovation». A personal response to the colloquium's principal themes', in D. Meeks and D. Garcia (eds), *Techniques et économie antiques et medièvales: le temps de l'innovation* (1998), 227–9; 'V. Gordon Childe and the vocabulary of revolutionary change', *Antiquity* 73 no. 279 (March 1999), 97–109; 'Technological innovation and economic progress in the ancient world: M. I. Finley re-considered', *Economic History Review* 53 (2000), 29–59.

[9] P. Millett, 'Productive to some purpose? The problem of ancient economic growth', in D. J. Mattingly and J. Salmon (eds), *Economies Beyond Agriculture in the Classical World* (2000), 17–48, at 31–4. Much of this argument (p. 33) consists of a rehearsing of instances where spectacular technology was applied to 'non-productive' uses in entertainment and religious festivals. In these cases, technology was being harnessed for the purposes of political power; this does not, of course, say anything about the use or lack of use of technology for economically productive ends.

[10] I will not attempt here to deal with siege engines, artillery, cranes, or transport technology and vehicles.

Banausis and Ancient Attitudes Towards Technological Innovation

It was a central tenet of the primitivist views of ancient technology that Greek and Roman intellectuals despised the practical application of science. Technology was a base art. Support is found for this view in a number of ancient authors and has been widely accepted, although there have been some dissenting voices in more recent scholarship.[11] The 'banausic' disparaging of technology is expressed most clearly in the story related by Plutarch about Archimedes, that he considered any practical application of his scientific research to be demeaning, and would not leave any treatise on his research (Plutarch, *Marcellus* 17.3–4). As with any anecdote, this incident must be treated with caution. Rather than reflecting a general attitude current in the ancient world, Plutarch relates it to show how odd Archimedes was — it forms part of an excursus on the character of Archimedes which lays stress on his preoccupation with pure theory, and makes out that his involvement in his scholarship was so total that he would forget to feed himself, neglect his personal hygiene, and would have to be dragged to the bath where he would trace geometric designs on the ground while others rubbed him down with oil (*Marcellus* 17.3–7). This is given partly as background to the story that Archimedes was killed by a Roman soldier, still absorbed in solving geometrical problems while Syracuse was sacked around him (*Marcellus* 19.4–6). Plutarch is not portraying Archimedes as a normal person, or even a normal scholar. That others took a very different view of technology is clearly brought out by the manner in which Plutarch introduces the subject of Archimedes' inventions: he says that Hiero of Syracuse persuaded him to turn his art from abstract theory to practical application, 'and by applying his philosophy to perceived needs to make it more intelligible to the masses' (*Marcellus* 14.4). Plutarch then goes on to describe mechanics as an art, 'now so celebrated and admired', and to say that it was Plato who had separated geometry and mechanics, insisting on a division between pure and applied science (14.5–6). Mechanics then (for a while) came to be regarded as a military art rather than a branch of philosophy — though Plutarch regards this as wrong. In other words, banausic views of technology existed among certain scholars, but not all, certainly in the fourth and third centuries B.C. but not necessarily at all periods; and those outside the academic community evidently took different views.

Similarly, there is Suetonius' story of the engineer who proposed to Vespasian an invention for hauling heavy columns up to the Capitol at little cost, evidently for an imperial building programme.[12] This was clearly some kind of machine; but Vespasian declined to use the device on the grounds that he needed to provide employment for the urban populace. This is commonly taken to show how social conditions retarded technological uptake; but the anecdote is actually more ambiguous. Significant, but overlooked, details are that Vespasian rewarded the engineer; and that while the need to provide employment for the urban poor was a pressing imperial concern at Rome, this was not necessarily the case in other areas of the Empire. Again, Suetonius' main point in the anecdote is to shed light on the character of Vespasian; this hardly allows us to conclude that such attitudes to inventions were characteristic of all emperors, let alone all Romans throughout the Empire.[13]

There is a fundamental problem with the evidence for attitudes to ancient technology, as almost all of it comes from the surviving literature, written principally by and for élites who in their attitudes to manual labour in particular are unlikely to be typical of the majority of the ancient population. Nor can we even assume that Greek

[11] K. D. White, '"The base mechanic arts"? Some thoughts on the contribution of science (pure and applied) to the culture of the hellenistic age', in P. Green (ed.), *Hellenistic History and Culture* (1993), 211–20.

[12] Suetonius, *Vespasian* 18: 'mechanico quoque grandis columnas exigua impensa perducturum in Capitolium pollicenti praemium pro commento non mediocre optulit, operam remisit praefatus sineret se plebiculam pascere.' 'To an engineer who promised to haul columns up to the Capitol at minimal expense, he offered no mean reward for his idea, but rejected the scheme saying he should allow himself to feed the plebs [i.e. by offering paid employment].'

[13] cf. a recent discussion of this anecdote in Greene, op. cit. (n. 8, 2000), 49–50.

and Roman intellectuals necessarily shared the same views; Posidonius,[14] Vitruvius, Frontinus, and Pliny the Elder took a very different line from Plato and Archimedes. Against Archimedes' refusal to write practical treatises on mechanics, we have to set the survival of a number of Hellenistic and Roman technical treatises, and the loss in late antiquity of many more.[15]

Modern Views of Ancient Technology and Attitudes Towards Investment

A key issue of debate in the last decade has been the extent to which Roman landowners invested in improving their estates to maximize financial returns. Rathbone argues for a considerable degree of economic rationality exhibited by landowners in Egypt, on the basis of the Heroninos archive relating to the management of parts of a large third-century A.D. estate in the Fayum.[16] He stresses, among other things, the sophistication of the accounting system used for the estate, and the degree of investment in irrigation infrastructure, notably the digging of ditches and the purchase and maintenance of water-lifting machines. He sees one of the aims of the estate owner as the maximizing of profits from the estate.

By contrast, in a series of studies, Kehoe has argued that Roman landowners aimed to gain a steady income from their estates with minimal intervention, and that this was best done by leasing to tenants.[17] The tenants had little incentive to undertake capital investments to improve yields, and the result was a mode of operation which yielded a reasonably secure but sub-optimal income through rent; from the landowner's point of view a 'satisficing' solution which achieved a desired goal, where that goal was security rather than maximum profit. While Kehoe certainly presents much evidence to show that tenancy was widespread and indeed does seem to have been used by many landowners in pursuit of such economic goals, the conclusions he draws — that these were the economic goals of Roman landowners in general — do not follow. Kehoe has chosen datasets that will inevitably lead him to these conclusions about tenancy, because his data deal primarily with tenancy rather than with landowners' economic goals. Apart from the Heroninos archive (where he and Rathbone come to different conclusions), his datasets simply do not give information about slave-operated *latifundia* or estates run through bailiffs without leasing. The main source of evidence for his study on imperial estates in the Bagradas (Medjerda) Valley in Tunisia is a series of inscriptions documenting relations between the managers (*conductores*) of imperial estates and the tenants.[18] His study entitled *Investment, Profit and Tenancy* in fact looks almost exclusively at the legal texts relating to guardians managing estates on behalf of their wards.[19] He rightly concludes that guardians tended to adopt a policy of leasing estates and not undertaking risky or expensive investment, but does not see the implications of the fact that this pattern is a function of their position *as guardians*, who cannot themselves benefit directly from the estate's returns, and who need to avoid accusations of mismanagement of the estate. Texts about the legal duties of guardians tell us very little about a Roman landowner's attitudes to risk and investment when running an estate for his or her own profit.

The debate on investment and economic rationality seems to have been underpinned by the assumption that technological investment was unimportant — either because little significant advance was made in technology and therefore its application would have had little return, or because élite economic culture worked against

[14] Quoted by Seneca in *Ep.* 90 as holding different views to Seneca's own on the utility of applied science.

[15] On Hellenistic technical treatises, see e.g. M. J. T. Lewis, *Millstone and Hammer: the Origins of Water Power* (1997), 20–8, 38–57.

[16] D. Rathbone, *Economic Rationalism and Society in Third-Century A.D. Egypt. The Heroninos Archive and the Appianus Estate* (1991).

[17] D. P. Kehoe, *The Economics of Agriculture on Imperial Estates of Roman North Africa* (1988); *Management and Investment on Estates in Roman Egypt during the Early Empire* (1992); *Investment, Profit and Tenancy. The Jurists and the Roman Agrarian Economy* (1997).

[18] Kehoe, op. cit. (n. 17, 1988).

[19] Kehoe, op. cit. (n. 17, 1997).

investment and so any technological advances that were made were not widely applied. This is one of the assumptions that the evidence presented below may challenge. A further assumption is that because ancient landowners did not measure profit and loss according to modern economic methods, they would have tended not to make capital investments because they could not accurately predict the return.[20] This does not seem to have acted as a universal deterrent: Suetonius tells us that the expense for the drainage of the Fucine Lake was borne by a group of investors in return for the reclaimed land.[21] At Kasserine in the Tunisian steppe, the verse inscription on the mausoleum of T. Flavius Secundus proclaims how he was the first to import viticulture to the region, which necessitated the creation of an irrigation network.[22]

Like other research on the ancient economy, the study of investment in technology is limited by a lack of any of the figures that a modern economist would want to use. We do not know population, gross national product, or *per capita* production figures for the Roman world at even a single moment in its history, let alone a series over time. We cannot therefore test for growth numerically or demonstrate whether, if growth happened, it might be attributable to the use of particular technologies. We cannot measure outcomes; we can only observe — in a very piecemeal fashion — the adaptational processes resulting from the adoption of technology, and we must seek to reconstruct the motives for those adaptations — whether, for example, these might be a response to labour shortage, or a desire to maximize profits. We cannot, for example, reliably estimate construction, operational, and maintenance costs for a water-mill and compare those with costs for an animal mill, or compare the returns from either kind of mill.[23] Often we are reduced to pointing to examples that may indicate how widespread was the use of particular technologies, and frequently the scale of investment can only be gauged by looking at the size of archaeological remains of a particular installation or activity. Imprecise as this approach is, it can nevetheless yield important results; studies by Mattingly and Hitchner have drawn attention to the colossal degree of investment in infrastructure for olive oil production in Africa and Tripolitania, where estate centres were equipped with multiple oil presses — three, four, or even more: eleven at Khirbet Aghoub in Numidia, nine at Henchir Sidi Hamdan in Tripolitania, and even a battery of seventeen presses at Senam Semana.[24] These purpose-built olive oil factories served estates engaging in cash crop production of olive oil, linked to overseas distribution tapping large Mediterranean-wide markets. On a regional economic scale, farms and villas in Latium and Southern Etruria show considerable evidence for investment in infrastructure (small aqueducts and large storage cisterns) for irrigated horticulture, doubtless to exploit the large market for fruit and vegetables provided by Rome.[25] Archaeological evidence can demonstrate something of the extent of a phenomenon, which may cause us to revise opinions based on documentary sources alone.

Although the lack of statistics limits the nature and precision of the conclusions we can draw, the evidence presented below — much of it archaeological — suggests that some mechanical devices were widely adopted in agricultural, mining and other sectors of the economy, and that these represent considerable capital investment undertaken with the deliberate aim of maximizing returns. There is evidence for such investment both by the state and by private landowners.

20 An assumption made by Kehoe in his review of Rathbone: 'Economic rationalism in Roman agriculture', *Journal of Roman Archaeology* 6 (1994), 476–84, especially 483–4.

21 Suetonius, *Claudius* 20.

22 *CIL* VIII.211, 52–4.

23 Even the data given in Diocletian's Edict on Maximum Prices (15.52–5) refer only to the costs of the mill-stones for animal- and water-mills (1500 denarii for a horse-mill, 1250 for a donkey-mill, 2000 for a water-mill, 250 for a hand-quern); not to the mill structure and associated works.

24 D. J. Mattingly, 'Oil for export? A comparison of Libyan, Spanish and Tunisian olive oil production in the Roman Empire', *Journal of Roman Archaeology* 1 (1988), 33–56; 'The olive boom. Oil surpluses, wealth and power in Roman Tripolitania', *Libyan Studies* 19 (1988), 21–41; R. B. Hitchner, 'Olive production and the Roman economy: the case for intensive growth in the Roman Empire', in M.-C. Amouretti and J.-P. Brun (eds), *La production du vin et de l'huile en Méditerranée* (1993), 499–508.

25 R. G. Thomas and A. I. Wilson, 'Water supply for Roman farms in Latium and South Etruria', *Papers of the British School at Rome* 62 (1994), 139–96.

WATER-LIFTING DEVICES IN HELLENISTIC EGYPT

Agriculture around much of the Mediterranean was and is heavily dependent on irrigation, and in many cases the topography requires that water be lifted out of wells or watercourses onto fields lying at a higher level. Water-lifting is highly labour-intensive, and the available labour largely determines the amount of land that can be cultivated. This is clearly an area where improvements in water-lifting technology can have an important economic impact: artificial irrigation in Egypt allowed watering the land more often than the once a year provided by the annual Nile flood; and multiple waterings allowed multiple crops to be grown per year.[26]

The earliest forms of water-lifting devices were the bucket and pulley, and the shaduf (Pl. I, 1); the former had a high lift but low capacity, the latter a lower lift but higher discharge rate. Both, however, demanded intensive human labour, and their effectiveness for irrigation was limited to terrain adjacent to and just above a watercourse. In the Hellenistic period, however, a new range of water-lifting devices was developed (Pl. I, 2–4) which revolutionized opportunities for irrigating land that could not be fed by gravity-flow irrigation systems. Several types of water-lifting wheel made their appearance — the wheel with compartmented rim, powered by men on a treadmill, by animals turning a capstan connected to the wheel by right-angled gearing (*saqqiya*), or by water turning paddles on the exterior of the rim (*noria*; Pl. II, 1); and the wheel with compartmented body, or tympanum, powered by men treading the outside of the wheel. The bucket chain, or chain of pots looped over a wheel, could also be powered either by men in a treadmill or by animals through right-angled gearing.[27] These inventions are anonymous; two further devices are attributed to named individuals — the force pump to Ctesibius (*fl. c.* 270 B.C.), and the water-lifting screw to Archimedes (*c.* 287–212/211 B.C.), although a recent theory argues that this was an invention of the ancient Near East which Archimedes merely refined and popularized.[28]

Michael Lewis' recent study, *Millstone and Hammer*, argues that many of these new devices were invented in the mid-third century B.C., probably at Alexandria. Evidence for this comes from the *Pneumatics* of Philo of Byzantium, a work surviving only in Arabic translation. Philo visited Alexandria around the middle of the third century B.C., and evidently met Ctesibius, but his *Pneumatics* seems to date from a little later, perhaps the 230s B.C., after he had left Alexandria.[29] The Arabic versions of the *Pneumatics* seem also to include material excerpted from Philo's lost *Hydragogia* or his *Mechanics*. Many of the sections dealing with water-lifting devices, water-powered automata, and even mentioning water-mills, have tended to be rejected by modern scholars as Arabic intrusions, on no better grounds than that the ancient world was not thought capable of such inventions at that date. Lewis in fact demonstrates that the letter sequences used to number details on the illustrations show that the relevant chapters are translations of the Greek and not Arabic intrusions; they lack the Arabic letter *waw*, used for the numeral 6 in new Arabic works, and many include *y*, translating the Greek ι, which is not used in letter series in Greek works after the time of Christ.[30]

According to chapters which on the evidence of their illustration letter sequences can be regarded as Greek, 'Philo seems to know of the bucket chain, overshot wheel, and perhaps the noria and the saqiya drive'.[31] But in a section whose authenticity has never been questioned, Philo clearly refers to animal-powered and water-powered lifting devices when he describes a large siphon for drainage purposes, a device which he says

[26] Rathbone, op. cit. (n. 16), 220.

[27] For ancient water-lifting devices, see Oleson, op. cit. (n. 6); J. P. Oleson, 'Water-lifting', in Ö. Wikander (ed.), *Handbook of Ancient Water Technology* (2000), 207–302.

[28] S. Dalley, 'Nineveh, Babylon and the hanging gardens: cuneiform and classical sources reconciled', *Iraq* 56 (1994), 45–58.

[29] For the dates, see Lewis, op. cit. (n. 15), 20–1. G. E. R. Lloyd, 'Hellenistic science', in F. W. Walbank, A. E. Astin, M. W. Frederiksen and R. M. Ogilvie (eds), *The Cambridge Ancient History* vol. VII.1 (1984), 326, 328 dates Philo to *c.* 200 B.C., and Ctesibius to the last quarter of the third century B.C.

[30] Lewis, op. cit. (n. 15), 26–36.

[31] Lewis, op. cit. (n. 15), 32.

is 'unknown to some who do not know how to lift water from these places except with buckets, as from wells, or with other devices that are moved and drawn by animals, or if perchance the extraction is to be done by means of the current of a river or spring flowing towards lower places'.[32]

That Philo was familiar with animal-powered and water-powered lifting devices seems to be confirmed by Lewis' analysis of Vitruvius' sources for his book on machines (*de Architectura*, Book 10). This indicates that Vitruvius relied on Philo of Byzantium for his descriptions of water-lifting wheels: he lists ten Greek authors who wrote on machines, of whom several can be eliminated on the grounds that they lived too early for such machines (fourth century B.C.), or wrote on other subjects (military or medical technology), leaving the unknown Diphilus and Democles, and Philo of Byzantium, Archimedes, and Ctesibius. Although Ctesibius wrote about his force pump, he did not write on other lifting devices, and Archimedes wrote only on the planetarium; 'therefore, by elimination, Philo was Vitruvius' source for the hodometer, screw, *tympanum*, *rota*, bucket chain, *noria* and water-mill'.[33] These water-lifting devices and other machines were therefore already known at the time Philo wrote, around the mid-third century B.C. or a little later. Although we do not know for certain that Philo wrote his *Hydragogia* or his *Mechanics* at Alexandria, the subsequent importance of the water-lifting devices in Egypt makes it highly likely that these machines, at least, were known at Alexandria in the mid-third century B.C., and very probably invented there.

If we can accept Lewis' arguments for placing the invention of this series of water-lifting devices, animal-powered and water-powered, in the decades 260–230 B.C., and that they were products of the Museum at Alexandria, we are led to ask: what drove this wave of technological advancement? The Museum is often seen as a pure research institute, producing little in the way of inventions that had any practical uses. However, the invention of water-lifiting devices that came into widespread use as irrigation machines, and the invention also of the water-mill at the same period, may suggest a programme of machine building related to agricultural development. At precisely this period, the middle of the third century B.C., settlement of the Fayum was intensified as a result of a change from the Ptolemies' reliance on mercenaries to a newly created class of Greek military settlers (*cleruchs*), who were given land grants but could be mobilized in an emergency.[34] Many of these were settled in the Fayum, and to achieve this a large programme of public works was undertaken to reclaim land by lowering the level of Lake Maeotis, and to extend the existing network of irrigation canals to the new fields.[35] Under Ptolemy II Philadelphos between thirty and forty new settlements were created in formerly uninhabited areas, with an artificial lake of 257 million cubic metres to irrigate 150 km^2 for a second harvest in the spring.[36] Agriculture in the Fayum depression is wholly dependent on irrigation, and water must be lifted out of the irrigation canals which are lower than the surrounding land — either by shaduf, or by more efficient machines. Is it simply coincidence, then, that the water-lifting wheel makes its first appearance in Egypt at this very time?

There was considerable royal concern for increasing agricultural productivity in the Fayum: Ptolemy Philadephos personally inspected Fayum around 252 B.C.,[37] and an important collection of papyri record various kinds of agricultural experimentation, including the introduction of new cash crops. This is the so-called Zenon archive, a collection of papyri belonging to the manager of a large estate in the Fayum given to Apollonius, finance minister under Ptolemy Philadelphos.[38] One papyrus of 256 B.C., (*P.Cair.Zen.* 59155) a letter from Apollonius to Zenon, says:

[32] Philo, 5, translated by Lewis, op. cit. (n. 15), 32.
[33] Lewis, op. cit. (n. 15), 46.
[34] N. Lewis, *Greeks in Ptolemaic Egypt: Case Studies in the Social History of the Hellenistic World* (1986), 24–5.
[35] N. Lewis, op. cit. (n. 34), 37–45.
[36] G. Höbl, *A History of the Ptolemaic Empire* (2001), 61–3.
[37] N. Lewis, op. cit. (n. 34), 44.
[38] C. Orrieux, *Les Papyrus de Zenon. L'horizon d'un grec en Egypte au III^e siècle avant J.C.* (1983).

> The king has ordered us to sow the land twice. Therefore as soon as you have harvested the early grain, immediately water the land by hand. And if this is not possible, set up a series of shadufs and irrigate in this way.

As this letter of 256 comes early in the suggested 260–230 B.C. window for the invention of water-lifting wheels, it is not surprising that Apollonius refers to the simple shaduf rather than *saqqiyas* or screws; but the link between royal intervention, irrigation infrastructure, and increased return is explicit.

Water-lifting devices such as the *saqqiya* and the *noria* were widely used in later Hellenistic and Roman Egypt. At some point, perhaps between the first and third centuries A.D., it seems that terracotta pots replaced wooden buckets on the *saqqiya*, doubtless making the machines more affordable, as wood was scarce and expensive in Egypt. These pots are frequently the key archaeological evidence for the use of the *saqqiya*. Both the papyri and finds of *saqqiya* pots imply that the use of the *saqqiya* increased during the early fourth century A.D., and it has been plausibly suggested that this relates to Diocletianic tax relief on irrigated land.[39] Here, then, we seem to have a situation where the state's aim of increasing agricultural output was achieved by encouraging private individuals to invest in irrigation technology via tax incentives.

In Roman times the *saqqiya* spread to other areas of the Mediterranean, certainly the Maghreb and probably Spain. A bucket chain device, using wooden buckets, was in use at Cosa in Italy in the later second century B.C., and the earlier of two bucket chain lifts recently discovered in London, in use for about ten years from A.D. 63, shows that this technology had reached Britain within twenty years of the Roman conquest.[40] These may either have been powered by men in a treadmill or by animals via a *saqqiya* drive. Although little has been published on *saqqiya* pots outside Egypt before the Byzantine period, a recent study makes it clear that the *saqqiya* was in use in Israel from the late second or early third century A.D. onward;[41] and more instances of early *saqqiya* pots may remain unpublished from excavations in the Near East and elsewhere.

Papyri from Roman and Byzantine Egypt make frequent reference to the hire, construction, or repair of such irrigation devices, and show that they were often an indispensable part of an estate — and might involve no small capital outlay.[42] The picture of the invention and spread of this technology outlined here suggests invention under the stimulus of a royal drive to increase agricultural yield, and a widening of uptake encouraged firstly by the reduced construction and repair costs resulting from the introduction of terracotta pots, and secondly by Diocletianic tax measures. Ultimately, the economic impact of this Hellenistic irrigation technology can be judged, in very crude terms, from the fact that it has been applied over much of the world in the twenty-three centuries since its invention. The *saqqiya* was widely used in medieval Islamic Spain, and was later carried to America, where it became sufficiently a part of rural life in the Wild West that one appears in the opening sequence of the Clint Eastwood film *The Good, the Bad and the Ugly*. *Saqqiyas* could still be seen in Spain in the 1960s,[43] and are in use in parts of Egypt today.

THE INVENTION AND DIFFUSION OF THE WATER-MILL

Apart from the use of the sail to propel boats by the wind, the water-mill represents the earliest human application of a natural force to do mechanical work. It is therefore of major importance in the history of technological development. Besides transforming

[39] Oleson, op. cit. (n. 6), 379–80.

[40] Cosa: Oleson, op. cit. (n. 6), 201. London: 'Roman water-lifting machinery unearthed in London', *British Archaeology* 62 (December 2001), 7. The second lifting device was found in a well dating to A.D. 108/9 and destroyed by fire perhaps between A.D. 120 and 130.

[41] E. Ayalon, 'Typology and chronology of water-wheel (*saqiya*) pottery pots from Israel', *Israel Exploration Journal* 50.3–4 (2000), 216–26.

[42] Rathbone, op. cit. (n. 26), 223–4.

[43] T. Schiøler, *Roman and Islamic Water-lifting Wheels* (1973), 16.

the process of milling grain into flour, it is also the remote ancestor of many other kinds of industrial machine which apply water-power to either rotary or reciprocating linear motion. It has also been something of a *cause célèbre* in the history of classical and medieval technology, having for many years been used as an illustration of the technological under-development of the ancient world.

The long-standing view that the water-mill, though known in the ancient world, had to wait until the early Middle Ages before it came into widespread use[44] has now been thoroughly exploded, although it is still sometimes peddled by medieval historians.[45] Michael Lewis has argued that the water-mill, in both horizontal and vertical forms, was an invention of the third century B.C.[46] Wikander has demonstrated that the widespread adoption of the water-mill occurred much earlier than used to be thought; the increase in the number of written references to water-mills from the fourth or fifth centuries onward is simply a function of the appearance — or survival — of new forms of evidence.[47] At the same time archaeology over the last twenty years or so has added substantially to the picture: in 1985 Wikander listed some forty-three water-mill sites from before A.D. 700 (of which thirty-two are Roman or Byzantine) and a further twenty-four stones or groups of stones that may derive from water-powered mills;[48] by 2000 his list of mill sites had expanded to fifty-six.[49] New evidence is accumulating all the time: to Wikander's lists can be added water-mills at München-Perlach (Bavaria), two in Narbonnaise, and two at Fullerton in Britain;[50] plus six mill-stones in the Musée St Germain (Paris), three in the Römisch-Germanisches Museum, Köln, six in the yard of the Aquincum museum (Budapest),[51] and two from Wantage (Oxfordshire, UK),[52] that must derive from water-powered mills, and four at Vindolanda that may do so.[53] To the literary references Wikander lists can be added a passage of Ammianus Marcellinus describing the preliminaries to the siege of Amida in A.D. 359, which evidently refers to a succession of water-mills in a narrow gorge forming the approach up the cliffs to the city from the Tigris below.[54]

Apart from a brief report on the identification of an allegedly first-century A.D. mill-wheel from Conimbriga (Portugal),[55] the earliest dated water-mill of which traces have been found is that at Chaplix (near Avenches, Switzerland), where the mill-race timbers have been dated by dendrochronology to A.D. 57/58, with repairs in the 60s; the mill's abandonment is dated from pottery and coins to the mid-Flavian period, *c.* A.D.

[44] e.g. Gille, op. cit. (n. 4); R. J. Forbes, 'Power', in C. Singer, E. J. Holmyard, A. R. Hall and T. I. Williams (eds), *A History of Technology* vol. 2 (1956), 589–622; R. J. Forbes, *Studies in Ancient Technology* vol. 2 (2nd edn, 1965); White, op. cit. (n. 4, 1962); Finley , op. cit. (n. 3).

[45] J. Gimpel, *The Medieval Machine. The Industrial Revolution of the Middle Ages* (2nd edn, 1992); F. Gies and J. Gies, *Cathedral, Forge, and Waterwheel: Technology and Invention in the Middle Ages* (1994); P. Malamina in preface to M. E. Cortese, *L'acqua, il grano, il ferro. Opifici idraulici medievali nel bacino Farma-Merse* (1997), 7–9.

[46] Lewis, op. cit. (n. 15); see above p. 7.

[47] Wikander, op. cit. (n. 7, 1984); see above p. 3.

[48] Wikander, op. cit. (n. 7, 1985 *History of Technology*).

[49] Wikander, op. cit. (n. 7, 2000).

[50] H.-P. Volpert, 'Die römischer Wassermühle einer villa rustica in München-Perlach', *Bayerische Vorgeschichtsblatter* 62 (1997), 243–78; J.-P. Brun and M. Borréani, 'Deux moulins hydrauliques du Haut Empire romain en Narbonnaise. *Villae* des Mesclans à La Crau et de Saint-Pierre/Les Laurons aux Arcs', *Gallia. Fouilles et monuments archéologiques en France métropolitaine* 55 (1998), 279–326. Fullerton: B. Cunliffe, *The Danebury Environs Roman Project. 5. Fullerton Villa Excavation 2001, Interim Report* (2001, unpub.).

[51] Personal observation, 1995 (St Germain — five stones on display and one in the reserves) and 1997 (Aquincum).

[52] N. Holbrook and A. Thomas, 'The Roman and early Anglo-Saxon settlement at Wantage, Oxfordshire. Excavations at Mill Street, 1993–4', *Oxoniensia* 61 (1996), 109–79.

[53] Personal observation, 1998.

[54] Ammianus Marcellinus 18.8.11; A. I. Wilson, 'Water-mills at Amida: Ammianus Marcellinus 18.8.11', *Classical Quarterly* n.s. 51.1 (2001), 231–6. The passage is textually corrupt and has hitherto defied interpretation by commentators and translators; but a simple emendation of *artandas* to *artatas* restores the sense.

[55] Identification by J.-P. Brun in 1997 of a supposedly first-century A.D. water-wheel 9 ft in diameter, found in the 1930s and now in the museum at Conimbriga: http://www.chron.com/content/chronicle/ae/art/9798/archives/0821portugal.html.

80.[56] Second-century A.D. mills are known from Germany and Gaul: a rural mill near Dasing in Bavaria is dated by dendrochronology to A.D. 103/112,[57] and the large complex at Barbegal, with sixteen overshot wheels on two mill-races, is now dated to the early second century A.D., rather than to the fourth century as used to be thought (Pl. II, 2).[58] From the Eastern Empire, inscriptions record tax revenue derived from water-mills at Beroe in Macedonia in the second century,[59] and a guild of water-millers at Hierapolis (Phrygia), *c.* A.D. 200.[60] The breakthrough of the water-mill had certainly occurred by the second century A.D., and almost certainly considerably before that: the construction of a water-mill in the mid-first century A.D. at Chaplix suggests that by then water-mills were already embedded in the economies of even fairly marginal parts of the Empire.

The diffusion of the water-mill around the Mediterranean and into northern Europe seems then to have occurred in the centuries between its invention, probably around the middle of the third century B.C., and the first century A.D. Lewis argues for the invention of the horizontally-wheeled mill in the region of Byzantium, and the vertically-wheeled mill at Alexandria.[61] In the Hellenistic world the diffusion of a new invention might well be slower than in the unified Mediterranean of the Roman world; and in pre-industrial societies the use of a new invention will often take a while to reach critical mass which would then ensure its rapid further spread. It would not therefore be surprising to find that the first century B.C. was just this period of increasing diffusion for the water-mill; Antipater's poem on the overshot water-mill, celebrating the labour-saving effect of the new device, should be read not as evidence that the water-mill was a new invention in the first century B.C., but that it was new to Antipater — whether he was writing in Greece, the eastern Mediterranean, or Rome.[62] It thus documents a moment in the spread of the technology to new regions.

In the Roman Empire, the army may have acted as one of the agents for spreading water-powered technology to the provinces — this was possibly the case in Britain, where two, and possibly three, sites on Hadrian's Wall had water-mills.[63] But the large number of mills in ordinary civilian contexts — rural and urban — from all over the Empire shows that the water-mill quickly became an integral part of rural life even in drier areas of the Mediterranean lands, where special types, such as the drop-tower mill driving a horizontal wheel by a jet of water exiting under pressure from a cylindrical reservoir 2–4 m high, were developed to exploit watercourses with feeble or unreliable

[56] D. Castella (ed.), *Le moulin hydraulique gallo-romain d'Avenche «en Chaplix»* (1994). A proposed first-century A.D. water-mill at S. Giovanni di Ruoti in southern Italy is unconvincing and is better interpreted as a latrine, with tiled splash-back for flushing with a bucket: A. M. Small and R. J. Buck, *The Excavations of San Giovanni di Ruoti*, vol. 1 (1994), 47–9, figs 22–7 pp. 305–9 and fig. 148 p. 429; cf. review by K. Greene in *American Journal of Archaeology* 103.3 (1999), 577–9. For latrines with tiled splash-backs, see G. C. M. Jansen, 'Water systems and sanitation in the houses of Herculaneum', *Mededelingen van het Nederlands Instituut te Rome* 50 (1991), 145–66, at 156–8.

[57] W. Cszyz, 'Eine baujuwarische Wassermühle im Paartal bei Dasing', *Antike Welt* 25 (1994), 152–4.

[58] P. Leveau, 'Les moulins romains de Barbegal, les ponts-aqueducs du Vallon de l'Arc, et l'histoire naturelle de la vallée des Baux (Bilan de six ans de fouilles programmées)', *Comptes rendus des séances de l'Académie des inscriptions et belles-lettres* (1995), 116–44.

[59] L. Gounaropoulou and M. B. Hatzopoulos, *Epigraphes Kato Makedonias*, vol. 1, *Epigraphes Beroias* (1998), no. 7 ll. A 28, 50, 85 and Γ 17, [20]. The second-century date is derived from the lettering style of the inscription (p. 108).

[60] H. W. Pleket, 'Greek epigraphy and comparative ancient history: two case studies', *Epigraphica Anatolica* 12 (1988), 25–37, at 27–8.

[61] Lewis, op. cit. (n. 15).

[62] Antipater of Thessalonica: Lewis, op. cit. (n. 15), 66–8; cf. A. Gauchéron, 'Who was Antipater?', in *The International Molinological Society. Eighth International Symposium on Molinology, Aberystwyth, July 3–10 1993. Conference Papers* (1993), 25–36. However, R. J. A. Wilson, 'Aqueducts and water supply in Greek and Roman Sicily: the present *status quaestionis*', in G. C. M. Jansen (ed.), *Cura Aquarum in Sicilia* (2000), 5–36, at 13–14, suggests that the Tremilia aqueduct at Syracuse, which terminates at the edge of a precipice on Epipolae, may have been designed to drive a water-mill; and that its technique of construction may suggest a date under Hiero II (270–215 B.C.). If so, this would represent a very early spread of the technique to Sicily. While this would be tempting in the light of what we know about the intellectual climate of Hiero's Syracuse, and his attempts to make Archimedes apply science to practical ends, both the suggested mill and the date remain hypothetical.

[63] Chesters (on the basis of a channel which is probably a mill-race) and Poltross Burn (for the nearby fort of Aesica): F. G. Simpson, *Watermills and Military Works on Hadrian's Wall: Excavations in Northumberland, 1907–1913* (1976). (The supposed mill at Willowford is in fact simply a bridge abutment; personal observation.) Powered mill-stones indicate a possible water-mill at Vindolanda, which certainly had a stream suitable for driving mills (personal observation).

seasonal flow.[64] In urban contexts the water-mill is found even in small towns like Saepinum, where an undated but certainly Roman mill near the forum was clearly powered off the aqueduct network.[65]

At several sites there are batteries of multiple-wheeled mills; the vast complex at Barbegal is well-known and has already been mentioned; doubtless it had some connection with the needs of Arles, but ownership and motives for construction remain unclear.[66] What is evident is that the capital cost of the complex must have been considerable: as well as the mill building (measuring 42 by 20 m in plan) and machinery (sixteen sets of overshot wheels and their millstones), it included the construction of an arcaded aqueduct branch derived from the main Arles aqueduct, and using perhaps half of its flow, that runs for 330 m across the Vallon des Arcs. But the capital investment must have been repaid by enormous production. The most recent estimates for the output of the Barbegal factory suggest perhaps 4.5 tonnes of flour per 24 hours, assuming 50 per cent downtime, sufficient to feed a population of 12,500 consuming 350 g bread per day each — or much of the population of Arles.[67]

These figures also give some indication of the scale of the advantages that water-mills had over animal-mills in terms of output rates. On Sellin's figures for Barbegal, the output per pair of stones is calculated at *c*. 24 kg per hour, which assumes that the millstones rotate at *c* 30 r.p.m.[68] The flour output is closely comparable to the performance of traditional overshot water-mills in Sweden[69] and Bosnia in recent times. A large overshot mill (with four wheels each driving one set of millstones) still operating at Livno in Bosnia grinds 20–30 kg flour per hour per set of stones, depending on seasonal levels of flow in the supply channel.[70] The approximate correspondence between output estimates for Roman mills and known figures for twentieth-century water-mills suggests that the major advances in water-powered milling technology had already been made by the Roman period, and that developments in the last 1,800 years of water-milling largely constituted refinements of an already mature technology. Figures for ancient animal-driven mills are hard to establish, but the rotational speed of the millstones (which is proportional to the throughput rate) must have been far lower than the 30 r.p.m. calculated for Barbegal; at a guess, a donkey might be hard pushed to sustain turning an hourglass-shaped *catillus* at even 6 r.p.m. (one revolution every ten seconds). On this basis, the output of an overshot water-mill with only one pair of stones may have approximately equalled that of five or more donkey-mills. Although the capital costs of a water-mill were clearly much higher, because of the greater complexity of the machinery and the necessary hydraulic engineering work on water-courses, they would have been to some extent offset by the fact that one pair of water-mill stones could do the work of several pairs of animal-driven stones; and of course the daily operating costs were much lower, without the need to feed or stable the animals, or employ people to drive them. Much of the time the millstones could run largely unattended.

Apart from Barbegal, the other massive complex of multiple mills in the Roman world was that on the Janiculum Hill in Rome. Remains of a mill complex on the

64 A. I. Wilson, 'Water-power in North Africa and the development of the horizontal water-wheel', *Journal of Roman Archaeology* 8 (1995), 499–510.

65 M. Matteini Chiari (ed.), *Saepinum* (1982), 172.

66 F. Benoit, 'L'usine de meunerie hydraulique de Barbegal (Arles)', *Revue archéologique* sixième série 15.1 (1940), 19–80; Leveau, op. cit. (n. 58); P. Leveau, 'The Barbegal water-mill in its environment: archaeology and the economic and social history of antiquity', *Journal of Roman Archaeology* 9 (1996), 137–53; P. S. Bellamy and R. B. Hitchner, 'The villas of the Vallée des Baux and the Barbegal Mill: excavations at la Mérindole villa and cemetery', *Journal of Roman Archaeology* 9 (1996), 154–76; A. I. Wilson, 'Deliveries *extra urbem*: aqueducts and the countryside', *Journal of Roman Archaeology* 12 (1999), 314–31, at 325–6.

67 R. H. Sellin, 'The large Roman water-mill at Barbegal (France)', *History of Technology* 8 (1983), 100–1.

68 A. T. Hodge, 'A Roman factory', *Scientific American* (November 1990), 58–64, at 60.

69 Anders Jesperson *apud* N. A. F. Smith, 'The origins of water power: a problem of evidence and expectations', *Transactions of the Newcomen Society* 55 (1983–4), 67–84, at 82–3, gives the output from an overshot mill on Fyn at 20 kg/hour.

70 The mill at Livno is owned and still (2002) operated by Janja Tomas. In the 1950s this mill used to grind flour for villagers from up to a day's travel around Livno, and a hostel was established in a building opposite the mill to accommodate customers of the mill overnight, illustrating how a facility such as this can generate its own knock-on service economy. I am very grateful to Helena Tomas for providing information about the Livno mill.

Janiculum have been known since 1886, in the Via G. Medici and the car park of the American Academy in Rome. Recent excavations have shown that this building, with two mill-races supplied directly off the Aqua Traiana, probably had four undershot wheels in series on its northern mill-race, and one larger wheel on the southern race.[71] It seems to have been built in the third century A.D., and destroyed around A.D. 400. But it now appears that it is probably merely an outlier of the main sets of mills recorded in various documentary sources — the fourth-century Regionary Catalogues, Prudentius, Cassiodorus, Procopius, and the Einsiedeln Itinerary.[72] It seems that the Aqua Traiana split into two branches just before it crossed the later line of the Aurelian Walls, and that the excavated mills lie on the southern branch, which was blocked in the Gothic siege of A.D. 537 to prevent the Goths from entering through it, and never unblocked. Subsequent references to the Aqua Traiana functioning within the city walls and driving mills on the Janiculum imply the existence of another branch, whose course must have been close to, if not identical with, that later taken by the Acqua Paola, the seventeenth-century Papal rebuild of the Traiana, alongside the old Via Aurelia running down to Trastevere. The main complex of mills — the *molinae* of the classical and early medieval sources — must lie under the modern Spanish Embassy and the Spanish Academy on the steep slopes below the seventeenth-century Fontanone of the Acqua Paola, and were probably overshot. It is very likely that there were also more overshot mills on the steeper section of the southern branch, in the gully of the Villa Spada,[73] although these cannot have been used after this southern branch was blocked. The excavated complex, using undershot wheels at the point where the Traiana's gradient starts to increase but before it becomes steep enough to use overshot wheels, looks like an attempt to squeeze in the maximum number of water-mills possible on this branch. The Janiculum, shown by the recent excavations to have been something of an artisanal district (dumps of waste from pottery and brick/tile kilns; glass cullet and metalworking slag; worked bone),[74] must also have been thick with water-mills on both branches of the Traiana, and perhaps the Alsietina as well.[75] The course of the two aqueduct branches exactly explains the peculiar configuration of the Janiculum salient traced by the Aurelian Walls at this point — Procopius tells us that the line of the Aurelian Walls on the Janiculum was intended to protect the water-mills there, which shows how vital they were to Rome's food supply by the late third century A.D.[76]

Coarelli has suggested that the mills on the Janiculum were built by Alexander Severus as part of a general reorganization of the *annona* — the corn dole for the urban *plebs* — which, between the late second and mid-third century A.D., moved from a distribution of grain to a handout of baked loaves. At some point in the same period the offices of *curator aquarum* (head of the water-supply network) and the *procurator Porticus Minuciae* (in charge of the grain/bread distribution) were merged. Since under the new system the state had to assume the functions of milling and baking, it is tempting to see this administrative merger as a move to facilitate the use of urban aqueducts as a power source for the *annona* mills, which were indeed driven off the Aqua Traiana. The overshot mills in the basement of the Baths of Caracalla must likewise have been built with state permission, if not ownership.[77] Coarelli interprets a remark in the *Historia*

[71] A. I. Wilson, 'Mulini, acquedotti e assedi sul Gianicolo', *Forma Urbis* 5.2 (Febbraio 2000), 32–7; 'The Water-mills on the Janiculum', *Memoirs of the American Academy in Rome* 45 (2001), 219–46. For earlier excavations of part of the complex cf. M. Bell, 'Mulini ad acqua sul Gianicolo', in S. Quilici Gigli (ed.), *Archeologia laziale XI* (1992), 65–72; 'An imperial flour mill on the Janiculum', in *Le ravitaillement en blé de Rome et des centres urbains des débuts de la République jusqu'au Haut Empire* (1994), 73–89.

[72] The *Curiosum* and the *Notitia*, ed. A. Nordh, *Libellus de Regionibus Urbis Romae* (1949); *Codex Theodosianus*.14.15.4 (Edict of Honorius and Arcadius, A.D. 398); cf. Wikander, op. cit. (n. 7, 1979), 21–3; Prudentius, *Contra Symmachum* 2.948–50 (A.D. 402); *CIL* VI.1711 (Edict of the City Prefect Dynamius, A.D. 475/488); Cassiodorus, *Variae* 11.39.1–2 (A.D. 533/537); Procopius, *Wars* 5.19.8–19 (events of A.D. 537); Einsiedeln Itinerary, ed. G. Walser, *Die Einsiedler Inschriftensammlung und der Pilgerführer durch Rom (Codex Einsidlensis 326): Facsimile, Umschrift, Übersetzung und Kommentar* (1987), 148–9, 183–4.

[73] Wikander, op. cit. (n. 7, 1979), 20, 26–7.

[74] Wilson, op. cit. (n. 71, 2001), 225–7.

[75] For a possible mill on the Aqua Alsietina on the Janiculum, see A. W. van Buren and G. P. Stevens, 'The Aqua Alsietina on the Janiculum', *Memoirs of the American Academy in Rome* 6 (1927), 137–46, at 139.

[76] Wilson, op. cit. (n. 71, 2001), for the detailed arguments. See also Wikander, op. cit. (n. 7, 1979).

[77] T. Schiøler and Ö. Wikander, 'A Roman water-mill in the baths of Caracalla', *Opuscula romana* 14 (1983), 47–64.

Augusta's life of Alexander Severus, to the effect that he built *opera mechanica plurima*, as a reference to the construction of water-mills.[78] The hypothesis is very attractive, although the exact dates of the three elements — the switch from handouts of grain to bread, the merger of the two offices, and the construction of the Janiculum mills — are not known with any precision, and may not have been exactly contemporary. Nevertheless, the fact that the Janiculum mills — the excavated complex and those others that must have existed further downstream — were driven directly from one of the main city aqueducts shows that their construction and operation can hardly have occurred without the involvement of the state, and they must have been connected with the *annona*. By A.D. 402 Prudentius links the operation of mills on the Janiculum with the handout of bread,[79] and this is effectively confirmed by Procopius' information about the relationship of the Aurelian Walls to the Janiculum mills, where the importance of the mills to the food supply was such that special defensive measures were necessary.

Multiple-wheeled mill complexes, or multiple sets of water-mills, are also known archaeologically from the Krokodilion river near Caesarea Maritima in Israel, and from Chemtou and Testour on the River Medjerda (the ancient Bagradas) in the fertile corn lands of northern Tunisia. At Caesarea there are up to four vertically-wheeled mills associated with the dam feeding the fourth-century low-level aqueduct.[80] At Chemtou and Testour two helix-turbine mill installations of almost identical type, each with three mill-races, seem to date also from the fourth century A.D. (Pl. III, 1). The wheels here were driven by tapering mill-races entering a circular wheelshaft tangentially, creating a swirling column of water that left the wheelshaft at a lower level. The horizontal wheels, which must have had angled blades, rotated fully submerged in a sort of artificial whirlpool, and acted as true turbines — a highly sophisticated design not paralleled again until 1577, in Spain. Combined with dams and offtake channels, this arrangement, requiring a drop of only 2 m, allowed the mills to run even when the water level in the river was fairly low in the summer months.[81]

Even though the mills at Caesarea Maritima are outside the town, it is clear that they must have served primarily the needs of the town, in the same way that the earlier complex at Barbegal must be related to nearby Arles; their location is determined by topographic and hydrological constraints. Less clear is who was responsible for their construction and operation — private individuals, or the municipalities? These late Roman multiple water-mills are large establishments representing a major capital outlay, and clearly designed to provide a very high output of flour. It is tempting, though currently unprovable, to connect them with the growth of municipal *annonae* in the provinces in late antiquity, which by the fourth century A.D. often involved the distribution of bread rather than grain.[82] An inscription from Sétif in Algeria, referring to the repair in A.D. 388/392 of a building which included ovens for baking the bread for the *annona*, may also have related to the repair of water-mills; the crucial word

[78] F. Coarelli, 'La situazione edilizia di Roma sotto Severo Alessandro', in *L'Urbs: espace urbain et histoire (Ier siècle av. J.-C.– IIIe siècle ap. J.-C.): actes du colloque international organisé par le Centre national de la recherche scientifique et l'École française de Rome (Rome, 8–12 mai 1985)* (1987), 429–56.

[79] Prudentius, *Contra Symmachum* 1.949–50:

> quis venit esuriens magni ad spectacula circi,
> quae regio gradibus vacuis ieiunia dira
> sustinet, aut quae Ianiculi mola muta quiescit?

[80] J. P. Oleson, 'A Roman water-mill on the Crocodilion river near Caesarea', *Zeitschrift des Deutschen Palästina-Vereins* 100 (1984), 137–52. A horizontally-wheeled mill by the same dam may be late Roman, but there are problems inherent in the dating techniques used; and the interpretation of this as a turbine mill is unconvincing; it may instead be a drop-tower mill of late or post-Roman type: T. Schiøler, 'Vandmollerne ved Krokodillerfloden', *Sfinx* 8 (1985), 12–14; 'The watermills at the Crocodile River: a turbine mill dated to 345–380 A.D.', *Palestine Exploration Quarterly* 121.2 (1989), 133–43, with comments in Wilson, op. cit. (n. 64).

[81] J. Röder and G. Röder, 'Die antike Turbinenmühle in Chemtou', in F. Rakob (ed.), *Simitthus* vol. 1 (1993), 95–102; F. Rakob, 'Der Neufund einer römischen Turbinenmühle in Tunesien', *Antike Welt* 24.4 (1993), 286–7; Wilson, op. cit. (n. 64).

[82] J. M. Carrié, 'Les distributions alimentaires dans les cités de l'empire romain tardif', *Mélanges de l'École française de Rome, Antiquité* 87 (1975), 995–1101, esp. 1070–86, 1090–4, presents evidence for municipal *annonae* involving bread distributions at Constantinople, Alexandria, and possibly Antioch, and points out that the corn dole archive at Oxyrhyncus suggests that they may have existed in smaller cities as well — a suggestion confirmed by *CIL* VIII.8480 cf. p. 1920 (= *ILS* 5596) from Sétif (unknown to Carrié), which clearly refers to baking bread for the *annonam publicam* (see below).

describing the building (a feminine plural noun) is lost, but the repairs involved the cleaning out of flood deposits (*inluviae*), suggesting an association with a watercourse.[83] Sétif had a local spring (and monumentalized fountainhouse),[84] and the potential for motive power was therefore present.

In the Eastern Empire, Hierapolis in Phrygia had a guild of water-millers around A.D. 200; tax revenue was derived from water-milling at Beroe in Macedonia in the second century A.D., and also at Antioch — where there was a municipal bread dole — in the fourth century.[85] Also in the Eastern Empire in the 320s, Orcistos successfully petitioned Constantine for elevation to municipal status, and the Imperial rescript (which doubtless repeated much of the original petition) cited among its other amenities and splendours a series of water-mills on a nearby stream; by A.D. 359 Amida also had a succession of water-mills in a gorge leading down from the city to the river Tigris below.[86] The lower operational costs and increased output of the water-mill had become widely recognized by the first and second centuries A.D., to the point where the device was in common use and in some cases substantial investment was made in the creation of large multiple-wheeled mill complexes, in connection with urban markets or with *annona* schemes. Although the use of animal-mills continued into the early Middle Ages, by the second century A.D., if not before, the water-mill had become an important feature of urban as well as rural life, with a certain political as well as an economic significance. And if the water-mill is seen as important for the medieval economy, the evidence now available for the Roman world suggests that it was important there too.

The Diversification of Water-power

Alongside the realization that water-power was widely used in the ancient world for milling grain has come newly discovered or recognized evidence that it was also applied to other purposes. The diversification of water-powered applications had long been thought a central feature of the so-called medieval industrial revolution.[87] Research on this topic has in fact produced some of the most egregious attempts to amend evidence to fit preconceptions. Some historians of medieval technology, concerned to minimize the picture of technological advance in the Classical world, even rejected evidence contrary to their views and then used the absence of such evidence to bolster their arguments for technological under-development in antiquity — a beautiful example of circular argument. Lynn White was so convinced that the ancients were incapable of using water-power for anything other than grist mills that he questioned the authenticity

[83] *CIL* VIII.8480 cf. p. 1920 (= *ILS* 5596): 'pro felicitate temporum beatorum [dominor(um)]| nostrorum Valentiniani Theodosi et [Arcadi] | aeternorum principum unum quo dd(ecuriones?) e[t] pr[inci]|pales ac cives gravi quatiebantur inco[mmodo molas ad annonam] | [p]ublicam a veteribus institutas omn[i renova|t]u operis ruinis inminentibus destit[ui detersa] | veteris squaloris inluviae adi[ecto novo] | cultu sua instantia reformavit [instrumento] | pistorio exornatas ad annon[ae publicae] | coctionem pistoribus tradi[dit et ita populum] | pavit Fl(avius) Maecius Constans v(ir) p(erfectissimus) praes(es) prov(inciae) | Mauretaniae Sitif(ensis) curam agente curatore | rei p(ublicae) splendid(issimae) col(oniae) Sitifensis.'
'For the happiness of the blessed times of our lords Valentinian, Theodosius and [Arcadius], eternal princes, Flavius Maecius Constans, eques, governor of the province of Mauretaniae Sitifensis, by the agency of the *curator rei publicae* of the most splendid colony of Sitifis, had restored at his instigation the one grave inconvenience by which the decurions and leading citizens and people were seriously troubled, [the mills ?] established by the ancients for the public [dole], with every repair of the structure which had been out of service and on the point of collapse, cleaned out the flood deposits of old filth and add[ed new] decoration, fitted them out with baking equipment for cooking the [public] dole, gave it to the bakers and so fed the people.'
Further discussion in A. I. Wilson, *Water Management and Usage in Roman North Africa: a Social and Technological Study*, D. Phil. thesis, University of Oxford (1997), 198, 200–1, 294–5.

[84] M. Bovis and L. Leschi, *Algérie antique* (1952), 155, 157.

[85] Hierapolis: Pleket, op. cit. (n. 60), 27–8. Beroe: Gounaropoulou and Hatzopoulos, op. cit. (n. 59), no. 7. Antioch: Libanius, *Or.* 4.29.

[86] Orcistos: A. Chastagnol, 'L'inscription constantinienne d'Orcistus', *Mélanges de l'École française de Rome, Antiquité* 93 (1981), 381–416, at 393–8 (dating) and 407–9 (mills). Amida: Wilson, op. cit. (n. 54).

[87] B. Gille, 'Machines', in C. Singer, E. J. Holmyard, A. R. Hall and T. I. Williams (eds), *A History of Technology* vol. 2 (1956), 629–58, at 638–45; White, op. cit. (n. 4, 1962), 79–84; Gimpel, op. cit. (n. 45), 13–16; Gies and Gies, op. cit. (n. 45), 114–15.

of Ausonius' *Mosella*, which mentions (ll. 361–3) water-powered marble saws near Trier in the fourth century A.D., an extreme position now thoroughly refuted.[88] Water-powered saws may also be referred to by Gregory of Nyssa, who refers to people sawing marble with iron and water.[89] Recent studies by Wikander and Lewis establish a case for the diversified use of water-power in the Roman world, but show how little we still know about this question.[90] New discoveries may help flesh out the picture — a case in point is the recent identification by Jacques Seigne of a water-powered sawmill (with two four-bladed saws either side of a single wheel) for cutting stone into veneer slabs, in a sixth-century A.D. phase within the Sanctuary of Artemis at Jerash.[91] This discovery is of particular interest because the investment in mechanizing the sawing of veneer underlines the scale of spoliation of material from abandoned classical buildings in the late antique period; next to the remains of the wheel-pit were found two partly-sawn column shafts.

Lewis, from analysis of writings mentioning the cracking and hulling of barley in antiquity, makes a case for the use of animal-powered and water-powered grain-pounders, the latter using trip-hammers driven by cams (lugs on a rotating axle, like those in a musical box).[92] The cam itself is attested in water-driven automata from the third century B.C., so there is no inherent problem with the concept that the transference of rotary to reciprocating linear motion was applied in antiquity. Lewis is surely right that the passage in Pliny (*NH* 18.97), which mentions the use of water-power in the hulling and pounding (not the *grinding*) of grains must refer to water-powered pestles: 'maior pars Italiae nudo utitur pilo rotis etiam quas aqua verset obiter et mola' ('the greater part of Italy uses an unshod pestle and also wheels which water turns as it flows past, and a mill [or trip-hammer]').[93] What is particularly important about Pliny's evidence is his assertion that this technique was used *in most of* Italy.

Water-powered pestles for pounding grain are also referred to in a biography in *Vitae Patrum Jurensis*, in the life of St Romanus who founded the monastery of Condat in the Jura. The biography mentions Sabinianus the deacon, active some time between A.D. 435 and *c.* 460, who was in charge of the *molinae et pisae* which lay on the stream below the monastery. *Pisae* (pestles) is the reading of all the mss, although early editors, victims of their preconceptions about ancient technology, preferred needlessly to emend it to *piscinae* (fishponds).[94] If water-powered pestles, as well as ordinary water-mills, were being built in fairly remote parts of the Jura in the mid-fifth century, knowledge of their construction and use should have been sufficiently common to survive the troubled times of the early fifth century; this period does not seem a likely context for their invention, which should be earlier. Such a conclusion ties in, of course, with Pliny's evidence that water-powered trip-hammers for grain pounding were common in Italy in the first century A.D.[95] There is tantalizing evidence for the possible use of water-powered trip-hammers in metal-working, in the form of a large metal hammer-head with evident mechanical deformation on one face from Ickham in Kent, a site with several Roman water-mills (for grain) and much metal-working waste.[96]

The demonstration that the ancient world used water-power for purposes other than grain milling has several important implications. It shows that ancient engineers were capable of thinking in a sufficiently imaginative way to apply the same power source to several different purposes; and that they could transform rotary motion to

[88] White, op. cit. (n. 4, 1962), 82–3; refuted by D. L. Simms, 'Water-driven saws, Ausonius, and the authenticity of the Mosella', *Technology and Culture* 24 (1983), 635–43; 'Water-driven saws in late antiquity', *Technology and Culture* 26 (1985), 275–6; Wikander, op. cit. (n. 7, 1981), 99–100; Wikander, op. cit. (n. 7, 1989).

[89] Gregory of Nyssa, *In Ecclesiasten* 3; Wikander, op. cit. (n. 7, 1981).

[90] Wikander, op. cit. (n. 7, 1981); 'Industrial applications of water-power', in Ö. Wikander (ed.), *Handbook of Ancient Water Technology* (2000), 401–10; Lewis, op. cit. (n. 15).

[91] J. Seigne, 'Une scierie méchanique au VI^e siècle', *Archéologia* 385 (2002), 36–7. I am very grateful to Jacques Seigne for discussing the evidence with me in advance of publication.

[92] Lewis, op. cit. (n. 15), 84–8, 101–5.

[93] Lewis, op. cit. (n. 15), 101–5. The interpretation of *mola* as trip-hammer is suggested by a fragment of Pomponius; see Lewis, op. cit. (n. 15), 94.

[94] Lewis, op. cit. (n. 15), 101–5; *Vita S. Romani* 52 and 57 (F. Martine, *Vie des pères du Jura* (1968), 296, 300): 'strenue in vicino flumine sub ipso Condatescensi coenobio molinas pisasque fraternis usibus gubernabat.'

[95] Lewis, op. cit. (n. 15), 101–5.

[96] Lewis, op. cit. (n. 15), 111.

reciprocating linear motion in order to do so. Grain milling was not the only manufacturing process to benefit from mechanization. As we shall shortly see, the conversion of rotary to reciprocating linear motion was also being applied in the first and second centuries A.D., on a very impressive scale, in the mining industry for crushing ore.

MINING AND THE ECONOMY

Several forms of water-power were exploited in mining. In the Laurion silver mines the Greeks had used automatic techniques of sorting crushed ores by playing water over them on stepped washing tables, so that the heavier, more metalliferous particles were left behind while progressively less metal-rich fragments were washed further down the tables according to their densities. These procedures were also used in Roman mines,[97] but the Romans went further and mechanized practically every stage of the processes of prospection, extraction, and primary ore-processing. Indeed, Roman mining, particularly in the gold and silver mines of the Iberian peninsula, saw some of the most advanced and large-scale applications of technology to economically critical work ever to be practised before the European industrial revolution, and some of the most impressive investment in infrastructural engineering works.

Mining Techniques

Primary deposits of metal ores generally occur as veins in the hard rocks of mountainous regions, and mining in such areas usually took place by means of shafts and underground galleries, a working method which is arduous and poses problems of ventilation, drainage, and the risk of tunnel collapse. The most profitable deposits to be worked were often therefore secondary deposits, where vein ore had been eroded out of the mountains and occurred as placer deposits either in high-level alluvium or in rivers or streams lower down. The exploitation of these surface deposits does not necessitate deep underground mining; furthermore, in the case of auriferous deposits, they contain much higher proportions of free gold, which makes their treatment easier.[98] But working such deposits requires investment in considerable technological infrastructure, often of staggering proportions. The technique used, hydraulic mining, effectively accelerates natural weathering processes by artificial means, using the erosive power of water to do the bulk of the work, and enabling operation on a phenomenal scale. In some cases this was also used in hard-rock mines to expose primary deposits where the overburden was up to *c.* 50 m thick, as at Puerto del Palo in north-west Spain.

The Romans seem to have been the first to develop techniques of hydraulic mining, namely hushing and ground sluicing (Fig. 1).[99] Both techniques are particularly well suited to secondary alluvial deposits, such as the gold-bearing alluvial deposits in north-west Spain. Hushing is a method of breaking up and removing the overburden to expose

[97] e.g. in Gaul — a wooden washing table found at Seix for washing lead ore (Daubrée, 'Aperçu historique sur l'exploitation des mines metalliques dans la Gaule. Notice supplémentaire', *Revue archéologique* 2ᵉ série 41.1 (1881), 201–21, 261–84 and 327–53, at 269 and fig. 14), and tiled washing channels from Massiac (L. Tixier, 'A Massiac (Cantal), une exploitation minière gallo-romaine', *Archéologia. Trésors des âges* 117 (Avril 1978), 30–7).

[98] On the terminology of deposits, see A. Woods, 'Mining', in J. S. Wacher (ed.), *The Roman World* vol. 2 (1987), 611–34, at 612–13.

[99] For overviews of hydraulic mining, see D. G. Bird, 'The Roman gold-mines of north-west Spain', *Bonner Jahrbücher* 172 (1972), 36–64; Woods, op. cit. (n. 98); P. T. Craddock, *Early Metal Mining and Production* (1995), 87–92; A. I. Wilson, 'Industrial uses of water', in Ö. Wikander (ed.), *Handbook of Ancient Water Technology* (2000), 127–49, at 140–2; D. G. Bird, 'Aspects of Roman gold mining: Dolaucothi, Asturias and Pliny', in N. Higham (ed.), *Archaeology of the Roman Empire: a Tribute to the Life and Works of Professor Barri Jones* (2001), 265–75. Woods, op. cit. (n. 98), 625–6, notes that the term 'hydraulicing', used in earlier publications for ground-sluicing, really applies to the modern method of excavation by water under high pressure from nozzles, and should be avoided in a Roman context.

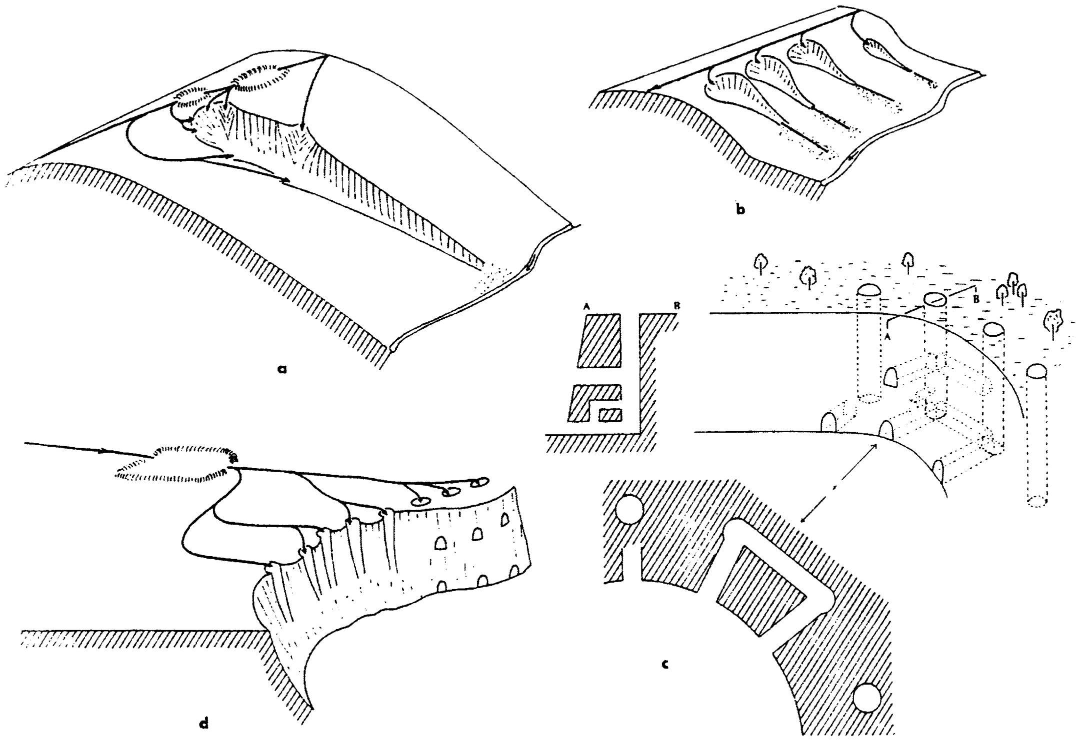


FIG. 1. METHODS OF HYDRAULIC MINING: (A) HUSHING; (B) GROUND SLUICING; (C) AND (D) *RUINA MONTIUM*, A VARIANT ON HUSHING WHERE ROCK-CUT TUNNELS WERE FLOODED TO BRING ABOUT THE COLLAPSE OF A WORKFACE. (C. Domergue and G. Hérail, *Mines d'or romaines d'Espagne: le district de la Valduerna (León)* (1978), fig. 35)

the deposit, by the periodic sudden release of water impounded in large reservoirs above the opencast. Considerable erosive force can be obtained — at Puerto del Palo (Pl. III, 2) the vertical face of the opencast is 200 m high and water released from the tanks at the top would have washed away almost anything in its path. Pliny's account of gold mining in Spain (*NH* 33.21.75) and those of nineteenth-century mining engineers talk of huge boulders being carried along hush-gullies by the force of the water.[100] Repeated scouring erodes the overburden, to expose the metalliferous strata, which can then be mined by hand or worked by ground sluicing.

Ground sluicing involves the continuous playing of a stream of water onto the alluvial deposit and over a sluice box or riffle, progressively breaking it up and — in the sluice box consisting of a series of stepped troughs — separating the ore from the alluvial gangue. This technique is particularly well suited to gold mining, as gold does not need to be smelted out of an ore; nuggets and particles are separated from the earth by washing. At Las Medulas de las Omañas in north-west Spain the results of massive-scale ground sluicing operations are visible as fan-shaped patterns of channels (Pl. IV).[101] These in fact probably represent prospecting in zones found to be unproductive, speculative investment that did not yield returns, which is why they have not been subsequently destroyed by wholesale extraction.

Both hushing and ground sluicing allow operation on a far greater scale than would be possible by purely human means, by harnessing natural forces to productive ends. But both demand the artificial supply of large quantities of water to the minehead, and it was here that Roman aqueduct technology came into its own. Pliny (*NH* 33.21.73–7) describes the prodigious efforts of workers at the Spanish mines to construct huge

[100] P. R. Lewis and G. D. B. Jones, 'Roman gold-mining in north-west Spain', *JRS* 60 (1970), 169–85, at 184; Bird, op. cit. (n. 99, 2001), 271.

[101] C. Domergue and G. Hérail, 'L'utilisation de la photographie aérienne oblique en archéologie et géomorphologie minières: les mines d'or romaines du nord-ouest de l'Espagne', in A. Bazzana and A. Humbert (eds), *Prospections aériennes: les paysages et leur histoire* (1983), 89–103.

industrial aqueducts over difficult and mountainous terrain, bridging gorges and crevasses and cutting through rock ridges, to supply water to huge hushing tanks above the opencast.

The scale of capital investment this represents is colossal, and Pliny stresses the enormous expense involved. From the 1970s onward, work on Roman mining in the Iberian peninsula has corroborated much of his description and shown that it is no exaggeration. Evidence for hydraulic mining is now known at many of the Roman gold mines of north-west Spain.[102] Many of the alluvial mines, and most of the hard rock mines of north-west Spain had more than one aqueduct for hydraulic mining.[103] Pliny (*NH* 33.21.72–3) describes techniques of breaking up the overburden by driving adits into the face of the opencast and then collapsing them, bringing down the rock face above — the so-called *ruina montium* technique, the results of which can be seen in the massive opencast workings, 2 km across, at Las Medulas (Fig. 2). The debris and collapse thus created could be removed by hushing, until the gold-bearing deposits below the overburden were exposed. At Las Medulas there are seven aqueducts (some 2–3 m broad, or two or three times the width of even the largest urban aqueducts) with a 400 m difference in elevation between the upper and lower systems. Their sources lay over 20 km distant from the mine as the crow flies; probably *c.* 50 km along contours. The aqueducts were for hushing to remove the overburden and then ground sluicing to work the deposit itself. The hushing reservoirs measured up to 200 by 40 by 3 m deep (= 24,000 m^3). Some clue as to dating is given by a Neronian aureus found in a sluice.[104]

Puerto del Palo in north-west Spain is a high-altitude hard rock mine, where the gold occurs as a vein deposit in a quartz outcrop (Pl. III, 2). The main opencast is so vast it is easily mistaken for a natural formation — it is over 200 m deep; but a hushing tank on the lip of the opencast, 55 by 5 by over 3.5 m high, shows that it was created artificially by hushing. Three aqueducts were built, one of which brought water from a neighbouring valley through a rock-cut tunnel. The Pumarin aqueduct traverses an earlier opencast to the north, to work the main opencast from its north face. A spur probably served another opencast area to the north-west; beyond this a continuation may represent a short-lived and unsuccessful prospecting gully. Most of the mining here took place by hydraulic means; a single underground adit may represent the final stages of working.[105]

At Dolaucothi in southern Wales, similar techniques were used to work gold deposits, again with hushing tanks for working the alluvial deposits. These were fed by two aqueduct systems, from the Annell and Cothi rivers, and the hydraulic system continually evolved as areas of the mine were worked out and the aqueducts were rerouted and adapted to service new working areas.[106] Once the opencast was worked out or became too deep to drain effectively, hydraulic methods were supplanted by the more labour-intensive technique of mining in deep adits.

Occasional variations on these basic hydraulic mining techniques are found at some Spanish sites as a response to local conditions; at Fucochicos in the Duerna valley, where the main ore deposits were higher than the available water supply, water delivered by an aqueduct was used to undercut a cliff face to create an opencast in which debris could then have been worked by ground sluicing.[107]

The primary ore deposits, from which the alluvial and placer deposits had eroded out, occurred high up in the mountains and had to be mined either by opencast mining (as above), or by deep underground mining, in shafts and galleries. The limitation on

102 Lewis and Jones, op. cit. (n. 100); R. F. J. Jones and D. G. Bird, 'Roman gold-mining in North-West Spain, II: workings on the Rio Duerna', *JRS* 62 (1972), 59–74; Bird, op. cit. (n. 99, 1972); Woods, op. cit. (n. 98); C. Domergue, 'A propos de Pline, Naturalis historia, 33, 70–78, et pour illustrer sa description des mines d'or romaines d'Espagne', *Archivo español de arqueología* 45–47 (1972–74), 499–528; C. Domergue, *Les mines de la Péninsule Ibérique dans l'antiquité romaine* (1990).

103 Bird, op. cit. (n. 99, 1972), 48.

104 Lewis and Jones, op. cit. (n. 100), 174–8.

105 Lewis and Jones, op. cit. (n. 100), 178–81.

106 G. D. B. Jones, I. J. Blakey and E. C. F. MacPherson, 'Dolaucothi: the Roman aqueduct', *Bulletin of the Board of Celtic Studies* 19 (1960), 71–84 and pls III–V; P. R. Lewis and G. D. B. Jones, 'The Dolaucothi gold mines, I: the surface evidence', *The Antiquaries Journal* 49.2 (1969), 244–72; Bird, op. cit. (n. 99, 2001).

107 Jones and Bird, op. cit. (n. 102), 71–3.

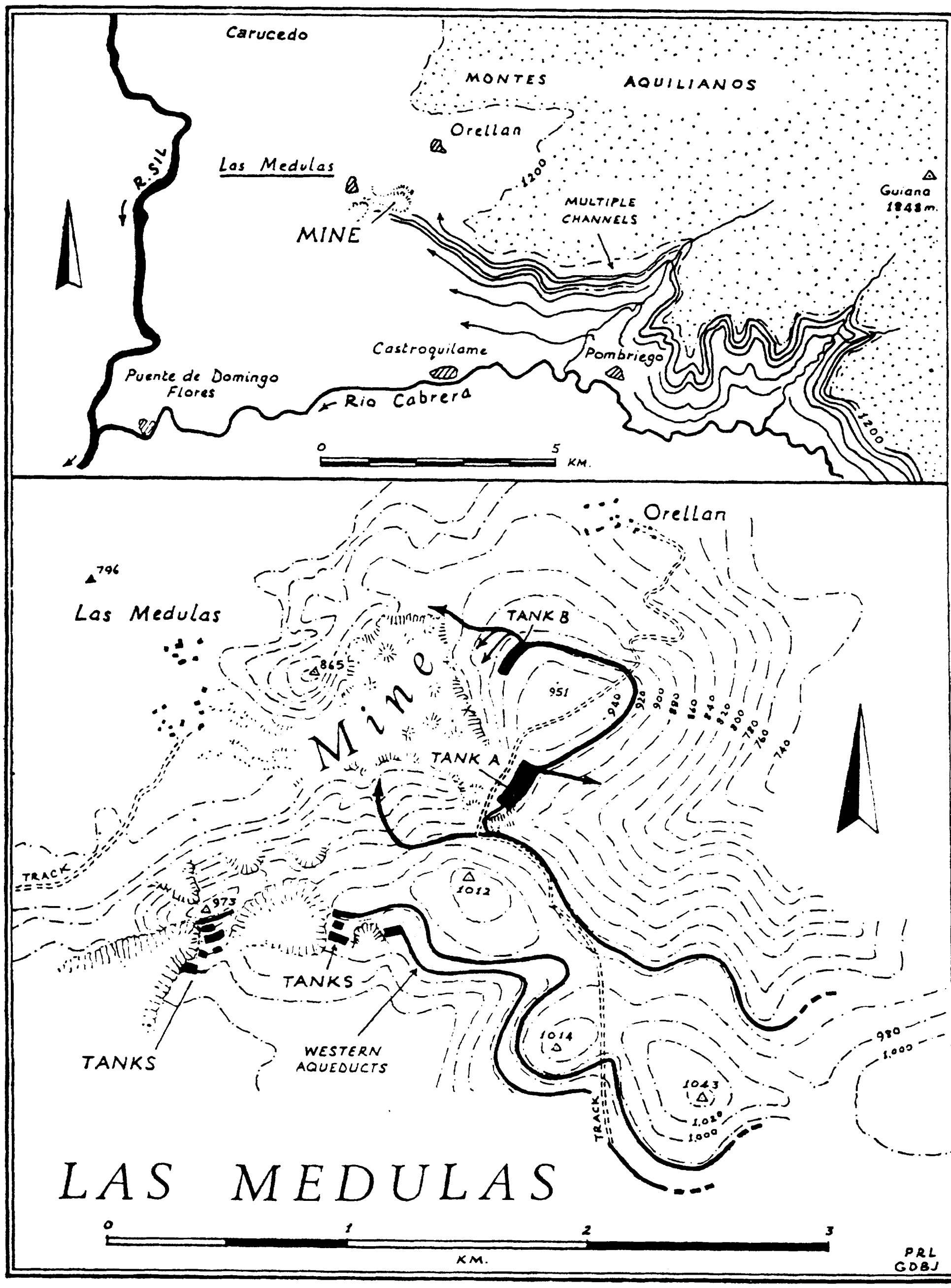


FIG. 2. PLAN OF THE MINING WORKS AT THE LAS MEDULAS GOLD MINE IN NORTH-WEST SPAIN. AQUEDUCTS LED WATER TO HUSHING TANKS ON THE EDGE OF VAST OPENCAST WORKINGS ACROSS A FRONT OF SOME 2 KM. THE SYSTEM CONSTANTLY EVOLVED AS THE WORKINGS PROGRESSED; THE TANKS AT BOTTOM LEFT HAVE BECOME SEPARATED FROM THE WESTERN AQUEDUCTS THAT FED THEM AFTER THE OPENCAST BELOW THEM WAS WORKED OUT, AND A NEW OPENCAST WAS OPENED UP TO THEIR EAST. (P. R. Lewis and G. D. B. Jones, 'Roman gold mining in north-west Spain', *JRS* 60 (1970), fig. 25)

activity in underground mines was the level of the water-table; mining could take place below the water-table only if drainage machines with suitable output capacity could prevent the mine flooding. Here, Roman mining engineers made full use of the Hellenistic water-lifting devices discussed above, notably treadwheels and the Archimedes screw — more than fourteen known examples at five different mines in France and

Spain, including a battery of four screws in series at Posadas.[108] Treadwheel-operated wheels are attested at numerous Spanish sites including Rio Tinto (eight pairs of successive lifts), and also at Dolaucothi in Wales. Pliny mentions the drainage operations needed in a Spanish silver mine with a gallery a mile and a half long, in which men 'stand night and day pumping out the water in shifts measured by lamps and create a river' (*NH* 33.31.97).

In the galleries of underground mines the scope for using machinery to extract ore was limited, although Pliny refers mysteriously to a *fractaria machina* incorporating 150 lb weights, used for attacking hard rock in the adits (*NH* 33.21.72). In the Galeria dos Alargamentos at Três Minas an adit connecting one of the two vast opencast pits to the surface outside is evidence for what Lewis interprets as an early kind of Roman mine railway for the removal of ore in wagons: deliberately cut grooves in the floor of the adit, with a gauge of *c.* 1.2 m, and passing places at intervals.[109]

Ore Processing

Whereas the working of alluvial deposits generally allowed the gold to be washed out of its alluvial gangue, ore mined from deep veins had to be smelted, i.e. heated to melt the metal out of the rock. A necessary preliminary was beneficiation, the elimination of as much sterile rock as possible, to minimize the amount of dross in each smelting charge, thus reducing fuel requirements and time on heating unproductive rock. This involved three stages: first, the ore had to be crushed into pieces small enough to reduce to powder in a second stage of processing, by milling. The powder was then washed in stepped washing troughs, as in the Athenian mines in the Laurion area, to sort it by density so that only the heavier, more metalliferous particles were smelted. The first stage, ore-crushing, essentially involves smashing rocks into very very small pieces, and must have been one of the most labour-intensive parts of the entire mining operation. Mechanizing this process would ease a critical bottleneck affecting a mine's output.

In very recent years it has been recognized that some evidence found at many Roman gold and silver mines, in the Iberian peninsula and also in Wales, implies a mechanized form of crushing ore.[110] Stone anvils for crushing ore have been found at numerous Roman hard rock gold and silver mining sites; some of these have several

[108] Oleson, op. cit. (n. 6), 191, 200, 221, 249–50, 270–2.

[109] M. J. T. Lewis, 'Railways in the Greek and Roman world', in A. Guy and J. Rees (eds), *Early Railways. A Selection of Papers from the First International Early Railways Conference* (2001), 8–19, at 15; C. A. Ferreira Almeida, 'Aspectos da mineração romana de ouro em Jales e Tresminas (Tras-os-Montes)', in *XII Congreso Nacional de Arqueología, Jaen 1971* (1973), 553–62, at 559–60; J. Wahl, 'Três Minas. Vorbericht über die archäologischen Untersuchungen im Bereich des römischen Goldbergwerks 1986/1987', *Madrider Mitteilungen* 29 (1988), 221–44, at 229–30.

[110] References collected in Lewis, op. cit. (n. 15), 106–10; B. C. Burnham, 'Roman mining at Dolaucothi: the implications of the 1991–3 excavations near Carreg Pumsaint', *Britannia* 28 (1997), 325–36, at 333–5. Examples have been found by the hundred in north Portugal at Três Minas (where all datable material is from the first and second centuries A.D., with no evidence of activity continuing into the third century) and nearby Campo de Jales (where datable material is mid–late first century A.D.): A. de Mello Nogueira, 'Uma exploração de minas de ouro da época romana', *Revista de Arqueología* 3 (1936), 201–6, at 203; Ferreira Almeida, op. cit. (n. 109), 561–2 and fig. III; Wahl, op. cit. (n. 109), 230–2 and Taff. 41, 44a, 45a, 56a (ore-crushing), 239–44 (dating); J. Wahl, 'Três Minas: Vorbericht über die archäologischen Ausgrabungen im Bereich des römischen Goldbergwerks 1986/87', in H. Steuer and U. Zimmerman (eds), *Montanarchäologie in Europa* (1993); 123–52, at 141 and Abb. 19. Other *cudes* stones are reported from gold mines at Bachicón de Fresnedo (Allande, Asturias), Cecos (Ibias, Asturias), Castropodome, Andiñuela and Corta del Valladar de Pozos (Léon); El Molinillo (Ciudad Reale y Toledo): F.-J. Sánchez-Palencia, 'Los "Morteros" de Fresnedo (Allande) y Cecos (Ibias) y los lavanderos de oro romanos en el noroeste de la Península Ibérica', *Zephyrus* 37/38 (1984/1985), 349–59; F.-J. Sánchez-Palencia, 'La explotacion del oro en la Hispania romana: sus inicios y precedentes', in C. Domergue (ed.), *Mineria y metalurgia en las antiguas civilizaciones Mediterraneas y Europas* vol. 2 (1989), 35–49, at 41, 46, 49 and fig. 5 (misinterpreted as components of washing tables; but the edges of the blocks are too irregular to fit together in the manner postulated). Domergue mentions but does not illustrate anvil stones from gold mines at Las Rubias, Faidel and Nava de Ricomalillo, and silver/lead mines at Sortijón de Cuzna and Catrezo Rajado; but these, like the illustrated examples from Lomo de Perro, mentioned in the same paragraph, are anvils used in non-mechanical crushing operations (Domergue, pers. comm.; op. cit. (n. 102, 1990), 497 and pl. xxviib).

(usually four, but occasionally up to ten) regular parallel depressions which have been made by repeated stamping or pounding with hammers in exactly the same place (Fig. 3). Some such anvils (*cudes*) have indentations on more than one face, where they have been turned over and reused. An operator crushing ore by hand with a hammer could not produce such a pattern of indentations; his strike would vary and never hit in exactly the same place;[111] furthermore, the depth and size of the impressions demands a much heavier weight than a man could wield. Some form of mechanical stamp operating within a guided framework is therefore implied, and, although such a device could be animal-powered, water-power is a more likely alternative for two reasons. First, water-supply was plentiful at many mines, even those in hard rock mountainous areas; the aqueducts and hushing tanks built originally for prospecting and removing the overburden were switched to other purposes, including ore-washing, once the overburden had gone and extraction of ore began. Secondly, at the gold mine of Dolaucothi in Wales, an anvil of the same type, known as the Carreg Pumsaint, stands beside the pit for a water-driven wheel, by a platform that must have held a crushing machine. Nearby a pile of tailings and slimes, the residue from the crushing and washing, has been dated by recent work to the Roman period. No post-Roman mining phases are attested at Dolaucothi before the reworking of the Roman mines in the nineteenth and twentieth centuries, long after the first written topographic reference to the Carreg Pumsaint. All this amounts to — in my view — compelling circumstantial evidence for the use of water-powered stamp mills to crush ore, such as were used in medieval and later mining (Fig. 4); we have seen that the component parts of the technology — water-wheels, cams, and hammers — were already known in Hellenistic times. Gullies at the hard rock mines at Braña, Fresnedo, and Iboyo in north-west Spain may also have been used for driving ore-crushing machinery by water-power.[112]

Water-driven mills may also have been used in the next stage of ore-dressing, the grinding of the crushed pieces into pulverized powder for washing. Large mill-stones, possibly from water-powered mills, are reported from the lead mines at Seix (France), and a copper mine at Mont Marcus near Auriac (Aude), although few details are given.[113] Lewis and Jones illustrate a large circular millstone (misleadingly described as a quern) from Roman strata in excavations at Ogofau Lodge by the crushing area at the Dolaucothi mines;[114] no dimensions are recorded, but from the size of the scale in the photograph the stone appears to have a diameter of 60–70 cm, and the size of the eye and the presence of holes for fixing clamps connected to the spindle, as found on second-century millstones from Barbegal, suggest that this may not be a hand quern but a powered millstone.

The pulverized ore was then washed in stepped washing gullies or on washing tables, probably on the same principle as in the Laurion washeries, to sort it mechanically so that only the denser, highly metalliferous particles were taken for smelting to produce the metal.

[111] Contrast the irregularity of wear patterns on anvil stones from Lomo de Perro (illustrated in C. Domergue, *Catalogue des mines et des fonderies antiques de la Péninsule Ibérique*, vol. 2 (1987), pl. XLIa) with the regular wear on the *cudes* stones.

[112] Bird, op. cit. (n. 99, 1972), 44–5. *Cudes* from ore-crushing machines at Fresnedo are reported (but misidentified) by Sánchez-Palencia, op. cit. (n. 110, 1989), 41.

[113] Daubrée, op. cit. (n. 97), 269 (Seix): 'De grandes meules de granite et d'autres pierres dures ont été rencontrées dans le voisinage'; 271 and fig. 15 (Mont Marcus): a lava millstone 55 cm in diameter; fig. 15 shows no evidence of a handle socket, so this does not seem to be a hand-quern. Disc-shaped mill-stones like this are characteristic of water-mills; human- or animal-powered stones are usually hourglass-shaped with a steeper grinding profile. Rotary millstones for grinding ore, with a diameter of 60 cm, are also published from the gold mines at Três Minas (Ferreira Almeida, op. cit. (n. 109), 562 and fig. III; Wahl, op. cit. (n. 109), 232, and Taf. 45 b–e); but as here the lower stones are not pierced for the passage of a spindle, they probably functioned like large hand-querns, and were not water-powered.

[114] Lewis and Jones, op. cit. (n. 106), 263 and pl. L c. For other millstones from Dolaucothi, apparently of similar size, see Burnham, op. cit. (n. 110), 334, and pl. XXIX b.

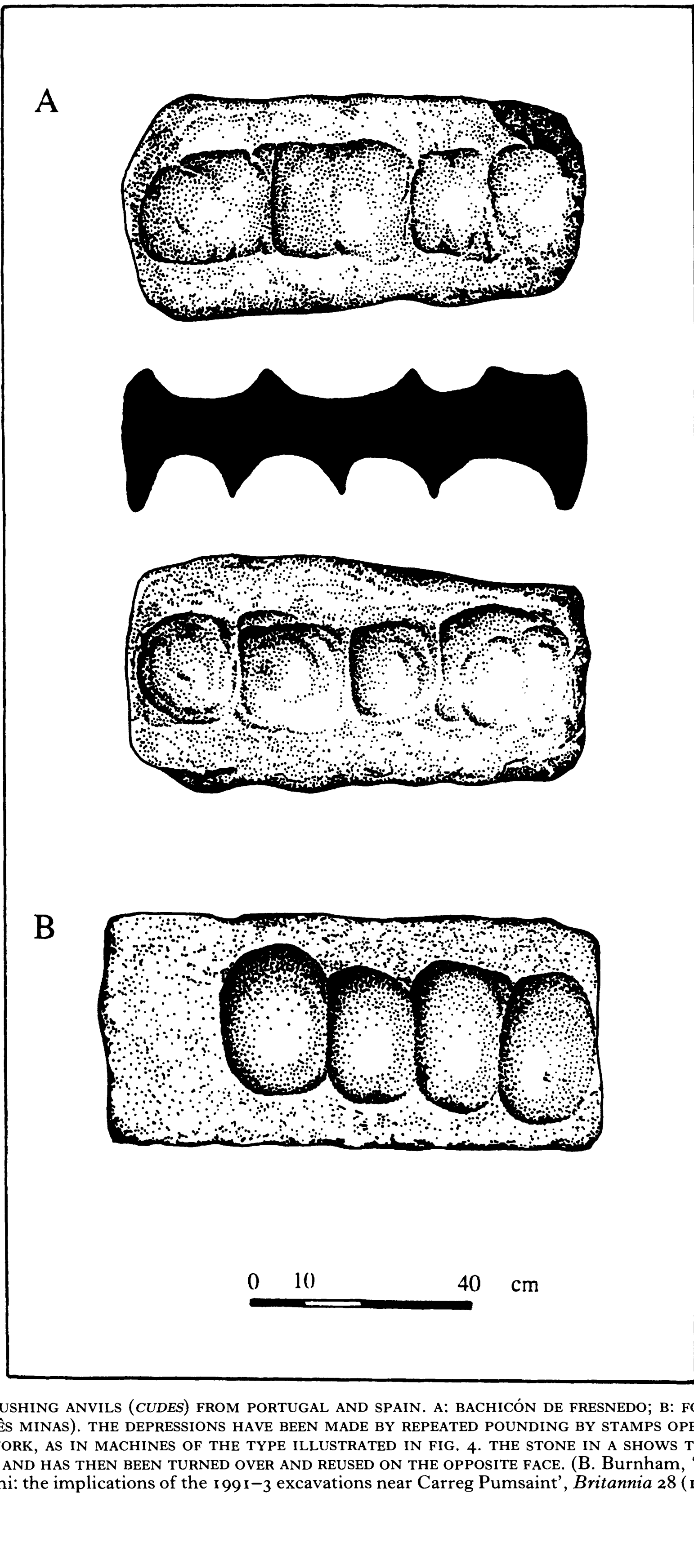


FIG. 3. ORE-CRUSHING ANVILS (*CUDES*) FROM PORTUGAL AND SPAIN. A: BACHICÓN DE FRESNEDO; B: FORNO DOS MOUROS (JALES, NEAR TRÊS MINAS). THE DEPRESSIONS HAVE BEEN MADE BY REPEATED POUNDING BY STAMPS OPERATING WITHIN A GUIDED FRAMEWORK, AS IN MACHINES OF THE TYPE ILLUSTRATED IN FIG. 4. THE STONE IN A SHOWS TRACES OF LATERAL REPOSITIONING, AND HAS THEN BEEN TURNED OVER AND REUSED ON THE OPPOSITE FACE. (B. Burnham, 'Roman mining at Dolaucothi: the implications of the 1991–3 excavations near Carreg Pumsaint', *Britannia* 28 (1997), fig. 4)

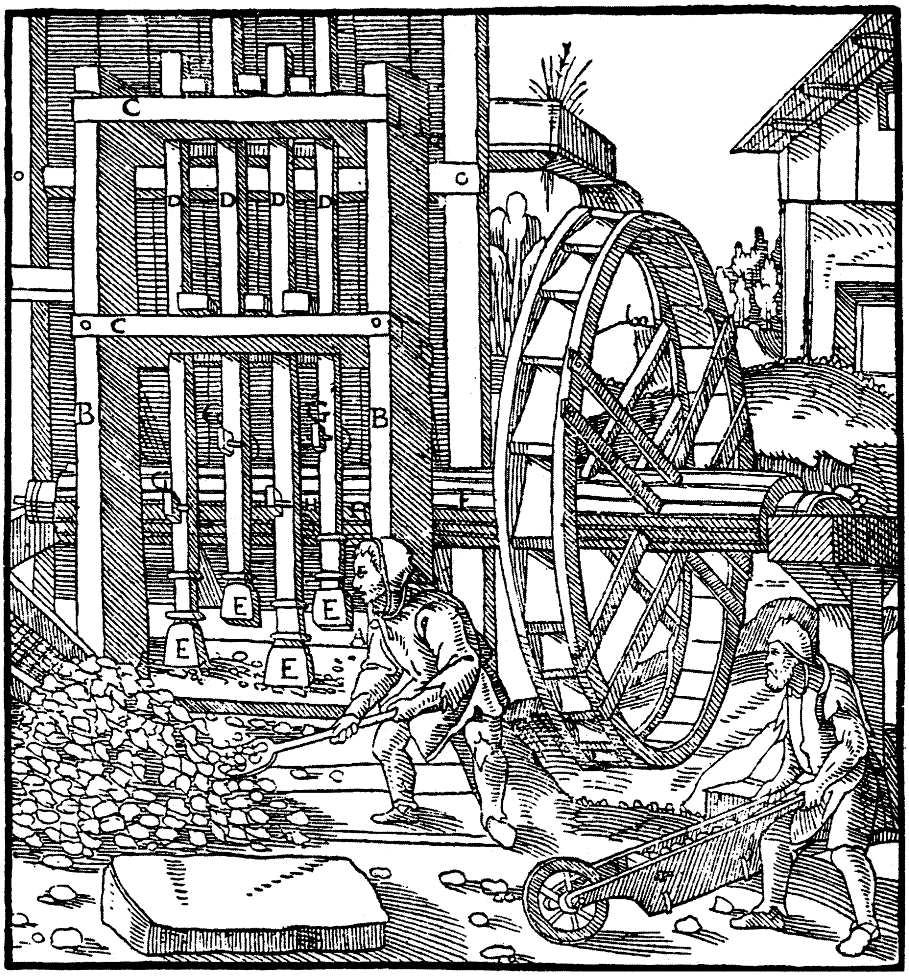


FIG. 4. MEDIEVAL ORE-CRUSHING MACHINE ILLUSTRATED IN AGRICOLA'S *DE RE METALLICA* (BOOK 8). AN OVERSHOT WATER-WHEEL TURNS AN AXLE ON WHICH CAMS RAISE AND DROP STAMPS SHOD WITH METAL HEADS (E) TO CRUSH ORE SHOVELLED ONTO THE ANVIL BENEATH THEM. THE STONES ILLUSTRATED IN FIG. 3 ARE ANVILS BELONGING TO A SIMILAR KIND OF MACHINE. (Georgius Agricola, *De Re Metallica*, translated by H. C. Hoover and L. H. Hoover (Dover Publications Inc. 1950), 284)

Economic Implications

Roman gold- and silver-mining, then, mechanized many of the labour-intensive processes involved. Water-power was used on a colossal scale to exploit alluvial gold deposits, and the erosive power of water removed the overburden in the operations of prospecting for vein ore, and then in making the veins accessible to opencast mining in some hard rock mines. In hard rock gold and silver mines water-power was used in ore-crushing and perhaps also to grind it; and then jets of water played over washing tables were used for the mechanical sorting of pulverized ore. These are applications of what must count, for any period up to the Industrial Revolution, as advanced technology, and they were applied on a truly industrial scale; operation on this scale was not attempted again until the nineteenth century. Clearly here the availability of slave labour did not retard technical progress; in some Roman mines, at least, we have a situation where slaves and condemned criminals were used and worked to death. The driving factor behind the mechanization of the Roman mines was surely a desire to maximize extraction rates rather than to reduce labour costs. This appears to be corroborated by a similar stress on ensuring maximum and continuous output in the second of two tablets found at Vipasca in Spain, governing the rights to exploitation of state-owned silver and copper mines there; articles 4 and 5 stipulate that a concessionaire must begin operation within twenty-five days of being granted rights to exploitation, and that if the mine is left inactive for ten days someone else may take over the workings.[115] The economic importance of the massive hydraulic gold mines in north-west Spain is underlined by the attention given to the military protection of the area, especially in the struggles for control of the Empire in A.D. 68–69.[116]

We would very much like to know more about the administration of the large hydraulic mines in Spain like Las Medulas. It is usually assumed that the larger Spanish mines were imperial estates worked directly by the state, and the evidence for military presence in north-west Spain in general and at some sites in particular may support this.[117] But at Dolaucothi in Wales mining activity continued after the abandonment of the auxiliary fort *c.* A.D. 130; while mining there apparently started under military supervision, it would seem to have been transferred to civilian operation in the second century. The Vipasca tablets and other evidence indicate that while the state owned the mines, they were often worked by *publicani* who rented the rights to exploit them; the state subcontracted the operation in a form of what we today call public-private partnership. If any of the larger mines were also operated in this way, then it follows that the hydraulic infrastructure and investment in crushing machines, mills, and ore-washing plant — all the material needed for operating the mines — was created by the *publicani*, by private individuals or by mining companies (*societates*). This would put the operation of large firms into a new perspective. And yet the existence of private operations of comparable size seems to be confirmed by Pliny's statement that a ruling of the censors prohibited the *publicani* who operated the gold mines of Victimulae in the territory of Vercellae in Northern Italy from employing more than 5,000 men (*NH* 33.21.78). Contractors in charge of mines on this scale must have accumulated considerable levels of personal wealth — one is led to wonder how many of the Spanish entrants to the Senate in the first century A.D. may have come from families with mining interests.[118] For the moment, though, the question of who provided capital for the hydraulic mines of north-west Spain remains unresolved.

We have seen some impressionistic index of the scale of production from the size of the opencasts; but work on the Greenland ice cores provides results that are, if anything, even more startling.[119] Atmospheric pollution from smelting operations in Roman-period silver, lead, and copper extraction has left its signature in Greenland ice cores, indicating a level of activity not paralleled again until the Industrial Revolution. Each year snow falls which does not melt and becomes compacted into ice; a cumulative permanent record is thus created which includes evidence for atmospheric conditions. Fig. 5 shows, in the lower line, the concentration of lead in Greenland ice as measured in twenty-one samples between 962 B.C. and A.D. 1523; there is a sharp peak in the sample for 79 B.C., with a sustained plateau in the Roman period until the early third century A.D., not exceeded again until the intensive exploitation of the German silver mines in the early eleventh century. The figures for the first century A.D. are markedly higher than for the second century A.D., and the third century A.D. onwards signals a low

[115] *Vipasca* II, ch. 4; see C. Domergue, 'La mine antique d'Aljustrel (Portugal) et les tables de bronze de Vipasca', *Conimbriga* 22 (1983), 5–193; S. Lazzarini, *Lex Metallis Dicta. Studi sulla seconda tavola di Vipasca* (2001) (*non vidi*). Opinion differs as to whether this law was more widely applicable; Domergue (op. cit., 153–71) argues that it was probably specific to Vipasca, and at most it could have been applicable only to the silver and copper mines of south-west Spain.

[116] R. F. J. Jones, 'The Roman military occupation of north-west Spain', *JRS* 66 (1976), 45–66, at 52.

[117] Jones, op. cit. (n. 116), 62.

[118] Domergue, op. cit. (n. 102, 1990), 330–1 for names attested on lead ingots of the first century from Spanish mines producing lead and silver.

[119] S. Hong, J.-P. Candelone, C. C. Patterson, and C. F. Boutron, 'Greenland ice evidence of hemispheric lead pollution two millennia ago by Greek and Roman civilizations', *Science* 265 (1994), 1841–3; S. Hong, J.-P. Candelone, C. C. Patterson and C. F. Boutron, 'History of ancient copper smelting pollution during Roman and medieval times recorded in Greenland ice', *Science* 272 (1996), 246–9; K. J. R. Rosman, W. Chisholm, S. Hong, J.-P. Candelone and C. F. Boutron, 'Lead from Carthaginian and Roman Spanish mines isotopically identified in Greenland ice dated from 600 B.C. to 300 A.D.' *Environment, Science and Technology* 31 (1997), 3413–6.

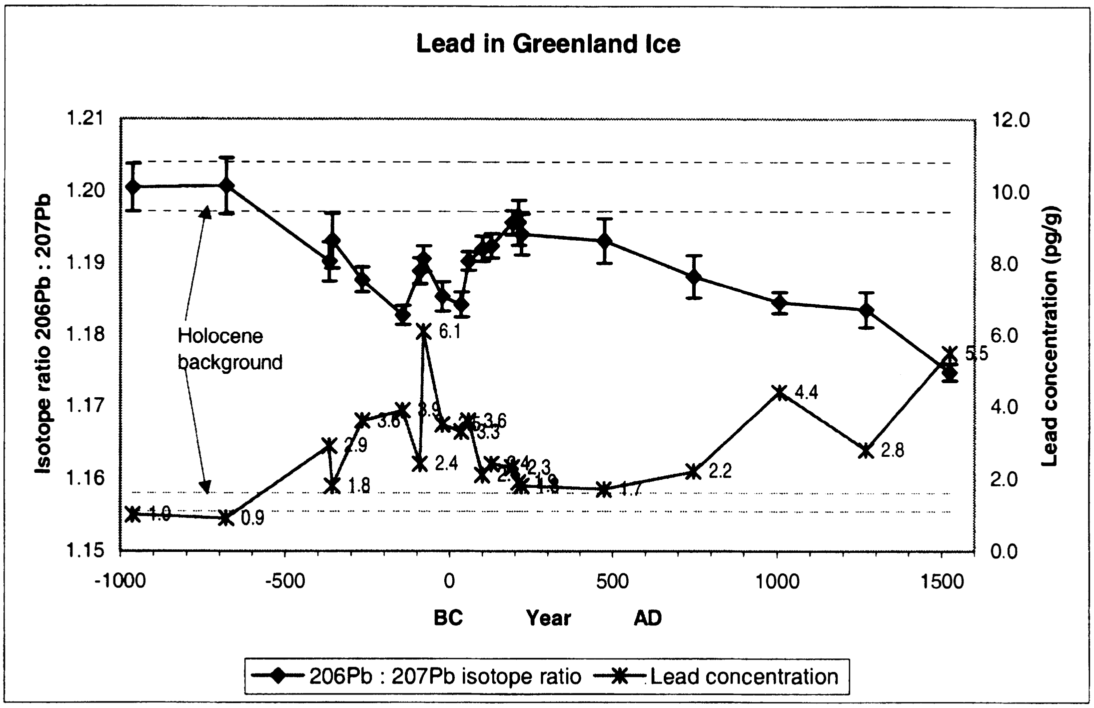


FIG. 5. VARIATIONS OVER TIME IN CONCENTRATION AND COMPOSITION OF LEAD IN ICE CORE SAMPLES FROM SUMMIT, CENTRAL GREENLAND. THE LOWER LINE SHOWS THE ABSOLUTE CONCENTRATIONS OF LEAD IN THE SAMPLES (PG/G) MEASURED AGAINST THE RIGHT-HAND VERTICAL AXIS. THE UPPER LINE SHOWS THE RATIOS OF ^{206}PB:^{207}PB ISOTOPES AGAINST THE LEFT-HAND VERTICAL AXIS, WITH UPPER AND LOWER ERROR LIMIT BARS (95% CONFIDENCE). THE DASHED BANDS REPRESENT THE RANGE OF VARIATION IN HOLOCENE BACKGROUND LEVELS FOR EACH SERIES, BEFORE ANTHROPOGENIC ACTIVITIES AFFECTED LEAD DEPOSITION. (Adopted with permission from K. J. R. Rosman, W. Chisholm, S. Hong, J.-P. Candelone and C. F. Boutron, 'Lead from Carthaginian and Roman Spanish mines isotopically identified in Greenland ice dated from 600 B.C. to 300 A.D.' *Environment, Science and Technology* 31 (1997); copyright 1997 American Classical Society)

approaching the Holocene background levels, with the recorded minimum in the late fifth century A.D. (the sample for A.D. 473). The upper line, showing the ratios of ^{206}Pb:^{207}Pb lead isotopes, confirms that these peaks are not due to natural variations in the atmosphere; the lead isotope signatures for the Roman period fall well outside the ranges for the Holocene background, and their variations mirror the concentrations of lead in the ice. Further isotopic analysis, measuring the ratios of ^{206}Pb, ^{207}Pb, and ^{208}Pb in the samples, suggests that during the Roman period around 70 per cent of this anthropogenically produced lead pollution may be related to smelting operations in south-west Spain.[120] This evidence shows unequivocally that during the Roman Republic and early Empire smelting activities from silver and lead mining created levels of atmospheric lead pollution high enough to be measurable over Greenland.

More striking still are the data from copper pollution, expressed in Fig. 6 as a change in the ratio of copper to aluminium in the ice cores. (The copper levels change while those of aluminium do not.) Here we can see that the levels of atmospheric pollution from copper smelting in the first century B.C. to second century A.D. were not exceeded again until the Industrial Revolution. On the basis of this, copper emissions to the atmosphere were estimated at 2000–2100 metric tons per year during the Roman period; and the actual metal produced must have been several times this.[121] The copper pollution may not derive from hydraulic mining activities; the higher levels of pollution may reflect a more polluting smelting process than that used in the production of lead and silver.

Roman mining technology therefore enabled massive metal extraction in the first and second centuries A.D. from mines in Spain and elsewhere, on a scale unparalleled

[120] Rosman *et al.*, op. cit. (n. 119).

[121] Hong *et al.*, op. cit. (n. 119, 1996).

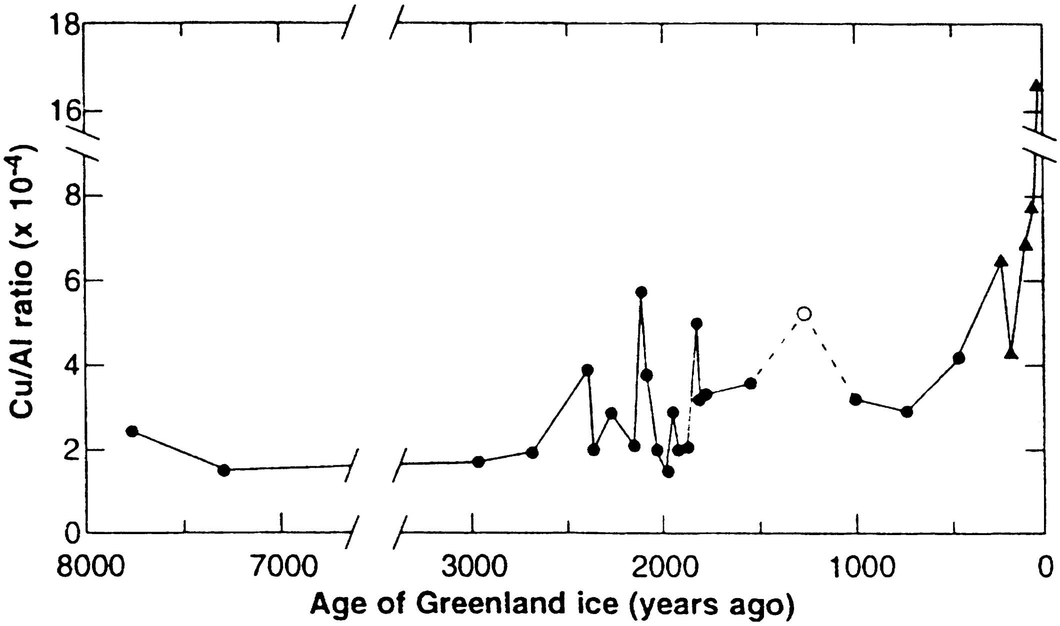


FIG. 6. CHANGES IN THE COPPER/ALUMINIUM RATIO IN GREENLAND ICE SAMPLES FROM SUMMIT, AS AN INDEX OF ATMOSPHERIC COPPER POLLUTION. (S. Hong, J.-P. Candelone, C. C. Patterson and C. F. Boutron, 'History of ancient copper smelting pollution during Roman and medieval times recorded in Greenland ice', *Science* 272 (1996), fig. 1)

again until the nineteenth century. Vast quantities of gold, silver, and copper were extracted from the Iberian mines and injected into the Roman economy as bullion for minting coin. According to Polybius (Strabo 3.2.10), in the mid-second century B.C. the silver mines of Cartagena in south-east Spain yielded 25,000 drachmae per day for the Roman state, or *c.* 35 tonnes per year; Pliny tells us that Asturia, Callaecia, and Lusitania together produced some 20,000 lbs weight of gold per year (*NH* 33.21.78).[122] While we cannot directly confirm such figures given by ancient authors, the Greenland ice core evidence and the scale of workings at the mines themselves certainly indicate colossal output. Under the Empire, hydraulic technology was critical to the scale of production achieved in gold and silver mining. In a very real sense, the Roman economy during the first two centuries A.D. was highly dependent on advanced technology and mechanization to keep the money supply going. We can begin to estimate the impact of this technology by looking at what happened after the mines in which this technology could be applied ceased production.

The debasement of the Roman silver coinage from the end of the second century onwards is well-known.[123] In the mid-first century A.D. the denarius had contained 97 per cent silver; in the late second/early third century a series of debasements reduced this to 40 per cent by A.D. 250, and further massive debasements took the silver content down to 4 per cent by A.D. 270. This is usually linked to the impact of the Civil Wars of A.D. 193–197, the increase in legionary pay under the Severans to retain the loyalty of the troops, and then, throughout the period until A.D. 260, a series of debasements caused by barbarian invasions, civil wars and the need to give donatives to the troops on the accession of a new emperor, which created a major drain on state finances in periods when new emperors seized the throne every two or three years. To meet the demand for new coin without raising taxes, the state melted down old coin, adulterated it with base metals and reissued more of it with a lower precious metal content; as the volume of

[122] R. Syme, 'Pliny the Procurator', *Harvard Studies in Classical Philology* 73 (1969), 201–36, at 218, supposes that these figures might relate to the reign of Augustus.

[123] M. Crawford, 'Finance, coinage and money from the Severans to Constantine', in *Aufstieg und Niedergang der römischen Welt* vol. II.2 (1975), 560–93; K. Hopkins, 'Taxes and trade in the Roman Empire (200 B.C.–A.D. 400)', *JRS* 70 (1980), 101–25, at 123.

coins minted increased, inflation rose, and the monetary system eventually broke down. This political explanation has much to commend it; but it is not the full story.

First, some debasement had been happening from the middle of the second century onwards. Secondly, the political/military pay explanation assumes that debasement is accompanied by an increase in the volume of coin produced; yet Hopkins' graph of the index of new silver coin supply calculated from data from several different regions of the Empire suggests that under Commodus, *before* the civil wars, new coin production actually fell, reducing new supply in Germany by 65 per cent from previous levels, in Britain by 50 per cent, and in Italy and France by 47 per cent.[124] Some factor other than demand for new coin to pay the army must also be operating.

Any discussion of the money supply needs to consider the bullion supply. Hopkins estimates that, during the period 157–150 B.C., silver stocks diminished by *c.* 2 per cent per year through coin loss and wear, except insofar as they were replenished by new metal. He declines to give a figure for the Empire, on the basis that debasement complicates the picture. The figure of 2 per cent is admittedly a guess, but it matters little whether the loss rate was 1 or 5 per cent.[125] A loss rate of 2 per cent would halve the volume of silver coin in circulation after just thirty-five years; if we assume a figure as low as 1 per cent, the volume in circulation would halve over seventy years. What little we know about trade in precious metals beyond the boundaries of the Empire probably suggests a net outflow of gold and silver, rather than the reverse.[126] In other words, replenishment by new metal is crucial to keeping coin in circulation. This is where the mines come in. We have no strong evidence for an increase in taxes to increase state revenues in the late second century; nor in this period is booty from foreign wars likely to be a significant source of metal. This leaves the bullion supply, the output from the mines, as our main variable.[127]

The mines of south-west Spain saw a hiatus in the later second century. The silver and copper mines of Rio Tinto were described by Barri Jones as the most important source of bullion in the early Empire on the basis of an estimated 15 million tons of visible silver and one million tons of copper slags at the site.[128] More recent work suggests that this is an over-estimate and the true figure may be nearer 6–7 million tons of slags,[129] but this nevertheless represents a colossal scale of production. The Greenland ice core evidence appears to confirm this, as the isotopic analysis suggests that the composition of lead pollution in Greenland ice is heavily influenced by isotopic signatures closely matching the Rio Tinto ores.[130] The extraction technology used at Rio Tinto is unfortunately obscure, as modern workings have destroyed much of the evidence and recording has been limited. However, there is as yet no evidence that the hydraulic techniques of hushing and ground sluicing were used here. Occupation of the Rio Tinto mining settlement and use of the cemetery stopped around the period A.D. 170–180. The reasons for this are not fully clear; the deposits were not exhausted. Barri Jones plausibly linked the abandonment with the Moorish invasions of Baetica in A.D. 171. Campaigns against the Moors continued until at least A.D. 177, with the Moors besieging the Baetican town of Singilia Barba; the area disrupted included Lusitania (with the silver and copper workings at Vipasca), and probably also Italica, north of Seville. There seems a strong likelihood that the Rio Tinto workings were disrupted during these incursions; at Vipasca the unusual title of *restitutor metallorum* (official in charge of reinstating mine workings), attested shortly after this, may be a consequence

124 Hopkins, op. cit. (n. 123), 113, fig. 4.

125 Hopkins, op. cit. (n. 123), 107–8. The figure of 2 per cent is based on C. C. Patterson, 'Silver stocks and losses in ancient and medieval times', *Economic History Review* (2nd ser.) 25 (1972), 205–35, at 207–10, who calculated a loss rate of 3 per cent for American silver coins in 1922–1962, and then guessed at a lower figure for the Roman Empire.

126 C. Howgego, 'The supply and use of money in the Roman world 300 B.C. to A.D. 300', *JRS* 82 (1992), 1–31, at 5–6.

127 M. Corbier, 'Histoire monétaire, histoire des prix, histoire des mines', in C. Domergue (ed.), *Mineria y metalurgia en las antiguas civilizaciones Mediterraneas y Europas* vol. 2 (1989), 183–94; Howgego, op. cit. (n. 126), 4–8.

128 G. D. B. Jones, 'The Roman mines at Riotinto', *JRS* 70 (1980), 146–65.

129 B. Rothenberg, F. Garcia Palomero, H.-G. Bachmann, and J. W. Goethe, 'The Rio Tinto enigma', in C. Domergue (ed.), *Mineria y metalurgia en las antiguas civilizaciones Mediterraneas y Europas* vol. 1 (1989), 57–70.

130 Rosman *et al.*, op. cit. (n. 119), 3415–16.

of this instability.[131] The picture is complex, but at around the time that many of the (non-hydraulic) silver and copper mines of south-west Spain seem to cease production, there is a spate of renewed activity at the hydraulic gold mines of the Duerna valley in north-west Spain (*c.* A.D. 180), though this activity barely seems to have extended into the third century. The reasons for the abandonment of the northern Spanish gold mines are wholly unclear; one might speculate that the army units who oversaw or protected the mines may have been withdrawn or moved elsewhere in response to other military needs. Jones tentatively suggested that the shift of focus in the late second century from the silver and copper mines of south-west Spain to the gold mines of the north-west might reflect a change in the relative importance of gold and silver bullion,[132] and this may be reflected in the shifting relative values of gold and silver charted by Duncan-Jones — both gold and silver coins became increasingly devalued from the reign of Marcus Aurelius onward, but the minting of gold remained more stable, with the result that the nominal gold:silver price ratio changed from 10:28 under Antoninus Pius to 5:51 under Severus Alexander.[133] In other words, the price of gold in terms of silver nearly halved, suggesting that while stocks of bullion in both metals had come under pressure, silver stocks were being squeezed harder. Few of the other Spanish mines show much evidence of occupation after around A.D. 190/200, and the main activity at Dolaucothi in Wales belongs to the first and second centuries A.D. The abandonment of the hydraulic mines of north-west Spain must have had a major adverse impact on the supply of metal, and therefore on state revenues and the money supply. Interestingly, Severus issued almost no bronze coinage from A.D. 199–209; and when it resumed, there was an increased reliance on using Greek mints to strike coin.[134] Does this reflect an increasing shortage of Spanish bullion?

While the immediate cause of the third-century debasements was the need to increase army pay and issue donatives with increasing frequency from the Severans onward, the debasement of the coinage cannot be considered in isolation from the wider question of the money supply, and the massive decline in production at the Spanish mines by *c.* A.D. 190 is a vital factor here. Although there were of course other sources of precious metals in the Empire, only in northern Spain did the geological conditions allow the phenomenal scale of extraction possible with hydraulic technology; mines elsewhere were generally in hard rock areas, tunnelled underground in shaft-and-gallery fashion, with correspondingly lower extraction rates. The loss of the Dacian mines, the major non-Spanish source of silver, in A.D. 258/9 may be related to the final stages of the debasements of the denarius. The need for more coin to service the demands of the army occurred just as the metal supply was being massively squeezed; debasement, and the adverse economic effects brought in its train, were inevitable.

The corollary is that, by contrast, the economic performance of the first and second century, and to a certain degree the high level of imperial or state spending — on the army, construction works, the *annona*, etc. — was partly dependent on the use of advanced technology and industrial-scale operation in the mines. The importance of technology to the ancient economy, and to wider historical processes, can be measured by what happened when the larger-scale hydraulic mining operations were no longer active.

[131] Jones, op. cit. (n. 128), 162; *Historia Augusta: M. Antoninus* 22.9–11. Mining at Vipasca continued into the second half of the third century A.D., with some evidence for occupation until the late fourth or early fifth century, although the extent of mining activity at this date is unknown (Domergue, op. cit. (n. 115), 31–2).

[132] Jones, op. cit. (n. 128), 163.

[133] R. P. Duncan-Jones, *Money and Government in the Roman Empire* (1994), 215–19.

[134] Crawford, op. cit. (n. 123), 564, 574–5.

CONCLUSIONS

Agriculture remained fundamental to the Roman economy, but the Roman Empire in the early centuries A.D. saw both aggregate and *per capita* economic growth,[135] and I believe this was due to significant technological progress, both in agricultural technology to sustain a greater number of non-agricultural workers in perhaps the most highly urbanized pre-industrial society the world has known, and in non-agricultural technologies, such as mining. Indeed, the economic boom of the first and second centuries A.D. is arguably partly attributable to the boost to state finances given by the use of advanced mining technologies, on top of a very healthy agrarian base which grew in the provinces under the stimulus of the opening up of new markets as vast swathes of territory came under Roman control.

Is that such an outrageous claim to make? Only if one remains wedded to the belief that because a very large proportion of the Empire's population was employed in agriculture (undoubtedly true), agriculture was so overwhelmingly dominant to the extent that fluctuations or improvements in other sectors of the economy made no appreciable impact on the overall picture (less true). I would rather argue that a healthy agrarian base was a vital platform on which — perhaps only for a limited period of two or three centuries — phenomenal rates of metal extraction allowed growth far above what would otherwise have been achievable.

On the Mediterranean-wide scale I see this happening under the Roman Empire; but the example of Classical Athens seems to confirm the phenomenon on a smaller scale. Fifth-century B.C. Athens fits ill with the idea that the ancient economy was largely agrarian, but this is usually passed over in silence. But Athens had an agricultural hinterland of very limited potential; relatively little land for grains, rather more for olives; but we know that most of its grain (and timber) had to be imported. The economic and political success of Athens in the fifth century B.C. rested on its silver mines and on the tribute it exacted from the Delian League in lieu of contributions of manned warships. This income in bullion and tribute enabled it to equip a navy and pay the crews — an early corollary to the Roman Empire's unique (for the period) practice of maintaining a standing army. It is difficult to see how the system of pay for Athenian democratic offices and for jury service could have been afforded on the basis of Attica's agricultural yield alone; the instruments of Athenian democracy and culture were funded from the Delian League and the Laurion mines. And the high yields from the Laurion mines were achieved in part by developing the sophisticated system of washeries using water pressure to sort the crushed ore, and thus increase recovery rates from the ore sent for smelting.

Recent archaeological work on ancient technology has revealed that considerable advances were made during antiquity in a number of areas, several of which were arguably of fundamental importance to the working of the ancient economy and are connected also with wider historical questions. The invention of geared water-lifting machinery in the third century B.C. made it possible to use animal power for irrigation of lands above a water-course; and the invention of the water-powered lifting wheel enabled automatic irrigation. Between them these types of machine facilitated intensive exploitation of the Fayum in response to the new landholding patterns entailed by the Ptolemaic use of *cleruchs*. These devices spread widely in the arid lands of the Near and Middle East, where they continued to be used well into the twentieth century. The use of water-power for milling grain seems also to have been invented in the third century

135 K. Hopkins ('Economic growth and towns in classical antiquity', in P. Abrams and E. A. Wrigley (eds), *Towns in Societies. Essays in Economic History and Historical Sociology* (1978), 35–77; op. cit. (n. 123)) makes a *prima facie* case for growth in the period 200 B.C.–A.D. 200 (cf. the qualifications of Millett, op. cit. (n. 9), arguing that most of such growth was probably concentrated in the final two centuries of that period). R. B. Hitchner (op. cit. (n. 24); '"The advantages of wealth and luxury": the case for economic growth in the Roman empire', in J. Manning and I. Morris (eds), *The Ancient Economy: Evidence and Models* (forthcoming 2002)) argues for intensive aggregate and *per capita* growth in the Roman period.

B.C., and was evidently widespread by the first century A.D. By the same time water-power had also been applied to driving other kinds of machinery, including machines requiring a back-and-forth or up-and-down linear motion, notably ore crushing in mining. There is also evidence for water-powered trip-hammers by the first century A.D., and for water-powered saws by the fourth century A.D. The use of all these various machines suggests capital investment in plant at a variety of social levels, evidently with an expectation that the greater output and lower running costs of water-powered machinery (over animal- or man-powered techniques) would recoup the higher initial outlay. It is particularly important that the widespread use of the water-powered grain mill in the Roman period cannot have been due to the feudal relations which are often held to be responsible for the water-mill's importance in medieval society — the obligation of unfree peasants to grind their grain at the lord's mill and pay *multure* (often one thirteenth of the flour) on it.[136] Sizeable milling complexes located in or near urban centres clearly catered to urban markets.

The diversified application of water-power was evidently not originally a medieval phenomenon, and many of the machines once thought part of the 'medieval industrial revolution' were to be found in the Roman world. But this is not to say that we should be talking instead of a 'first-century industrial revolution'; the tendency to try to find smaller-scale precursors of the real Industrial Revolution goes hand-in-hand with the false assumption that we need to explain why the Industrial Revolution did not happen in antiquity. The Industrial Revolution was not an inevitable result of technological progress; technological progress does not always lead to economic 'take-off', and sometimes stagnation or even regression occurs instead. Necessary but not sufficient preconditions for economic take-off are an intellectual climate open to technological development, and the availability of investors and capital. The archaeological, literary, and epigraphic evidence reviewed here suggests that these factors were available in the Roman world of the early centuries A.D., even if the diffusion of the water-mill may have taken two or three centuries from its invention to achieve take-off. But the radical difference between the scale of economic take-off observable in the first two centuries A.D. and that of the Industrial Revolution suggests that the Industrial Revolution demanded additional factors as well. This is not the place to explore these, although one might imagine that they included but were not limited to the greater potential and topographic flexibility of fossil fuels and the steam engine as compared to water-power (fossil fuels are a portable power source, and the steam engine can be mounted on a vehicle in a way that a flowing water source cannot); these factors could in turn enable greater diversity of applications, with a faster feedback process of cross-fertilization and consequent snowballing of development. Nevertheless, the use of water-power in water-lifting for irrigation, milling and other forms of machinery, and in hydraulic mining arguably did enable economic growth in the Hellenistic and Roman periods, and initiated the first steps towards mechanization. The principal breakthroughs in applying natural power sources to various forms of mechanical work had already been made by the late first century A.D., and until the discovery of new power sources with the Industrial Revolution, subsequent developments were largely variations on a theme. Even the medieval windmill (whether horizontal or vertical), the first exploitation of wind-power apart from the sailboat, was applied to tasks already performed by water-powered machinery. The use of hydraulic technology in Roman mining of the first and second centuries A.D. remained unsurpassed again until the nineteenth century. This enabled a certain amount of economic take-off for two centuries, but the technology was applicable only in certain regions and appears to have been ultimately unsustainable in the political conditions of the third century which made it too risky for either the state or private investors to undertake the colossal levels of capital investment in the necessary hydraulic infrastructure.

136 Gies and Gies, op. cit. (n. 45), 115–16, noting also the existence of independent water-mills not under feudal control.

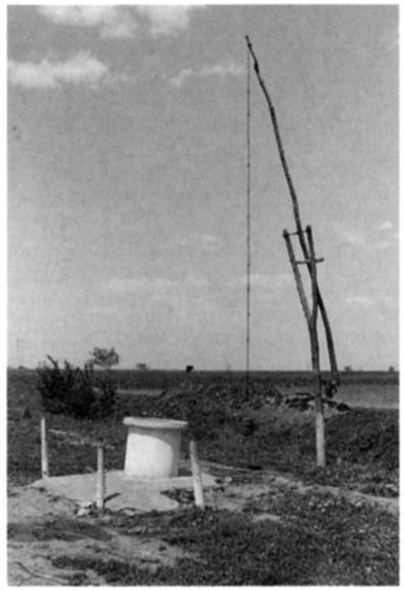
Availability of investment capital was clearly critical, and it is notable that the various technologies examined here appear to show a pattern of invention under royal or state stimulus, with uptake later on in the private sphere. The inventions of geared and water-powered water-lifting devices, and of the water-mill, seem to have occurred under Hellenistic royal patronage with the goal of increasing agricultural production. Later developments, including reductions in the cost of the *saqqiya* and tax incentives for its use, enabled the spread of such technology to lower levels of society. The advances in mining techniques in the early Roman Empire were clearly also driven by the economically vital nature of the enterprise and the availability of capital for such a high-return activity. The extraordinary levels of investment achieved by the state in the development and operation of Spanish gold mines enabled the proto-industrialization of mining within the limits afforded by the use of water-power; and the extraction rates achieved must have had a major effect on the bullion supply and hence on the coinage.

The Roman use of hydraulic mining techniques in the first two centuries A.D. and then the apparent abandonment of such techniques in the third century is an illustration of how technology may not always follow a linear pattern of advance. In the case of hydraulic mining the reason for the loss of the technology may be connected with the vast levels of capital investment necessary, as this is not a technique that can be applied on a small scale. An instance of technological regression that is less directly related to wealth creation but rather reflects a wider economic situation is the apparent cessation of construction in fired brick (and concrete) north of the Alps from about the fifth century onwards. This is presumably explained by a massive contraction in the building industry; in fifth-century North-West Europe construction projects were no longer being undertaken on the scale or with the frequency that made it worthwhile to mass-produce standardized building components, either for the market or for specific projects. Similarly, the loss of the use of the potter's wheel in post-Roman Britain seems to reflect the end of mass-production of even such a humble commodity as pottery, and the shrinking horizons of pottery distribution networks. Because bricks and the potter's wheel are two very basic technologies where the level of capital investment required is low, their loss for several centuries is all the more revealing about the level of economic change in late antique and early medieval northern Europe.

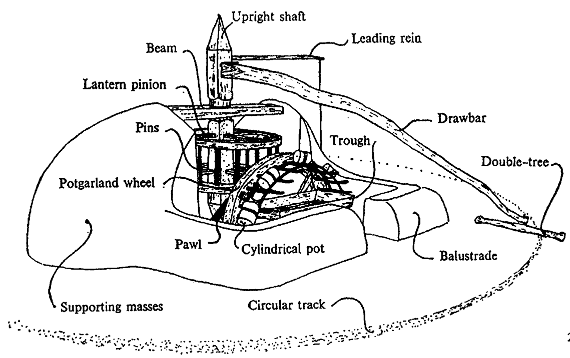
Much more work remains to be done on the part played by technology in the economy of the ancient world, but the examples I have looked at here, water-lifting, milling, and mining, show the importance of understanding the role of technology, and its diffusion and adoption, in interpreting economic patterns, processes of settlement expansion, agricultural production, and the development of political instruments such as the *annona* to gain or maintain popular support. It is time to return the study of ancient technology to the mainstream of history.

Institute of Archaeology, Oxford

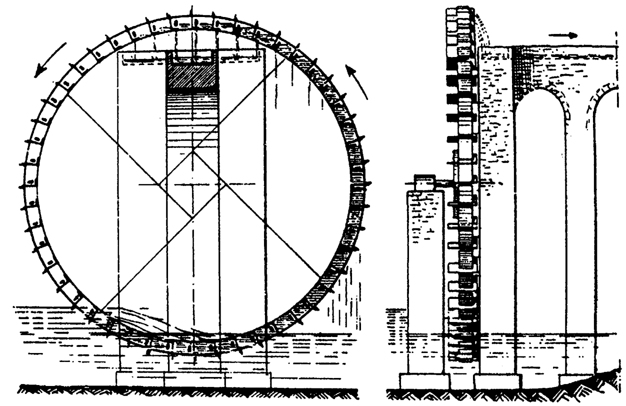
andrew.wilson@archaeology.ox.ac.uk



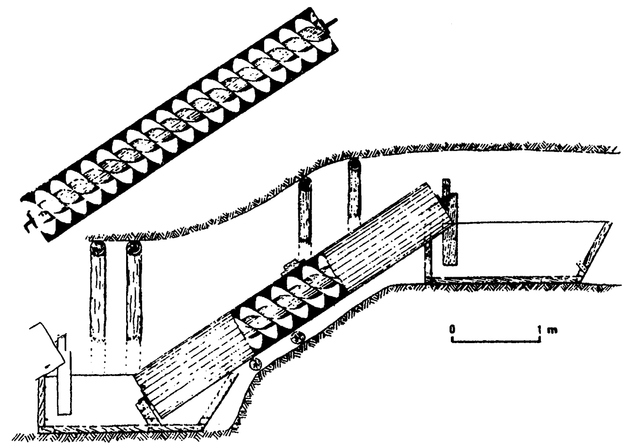
1



2

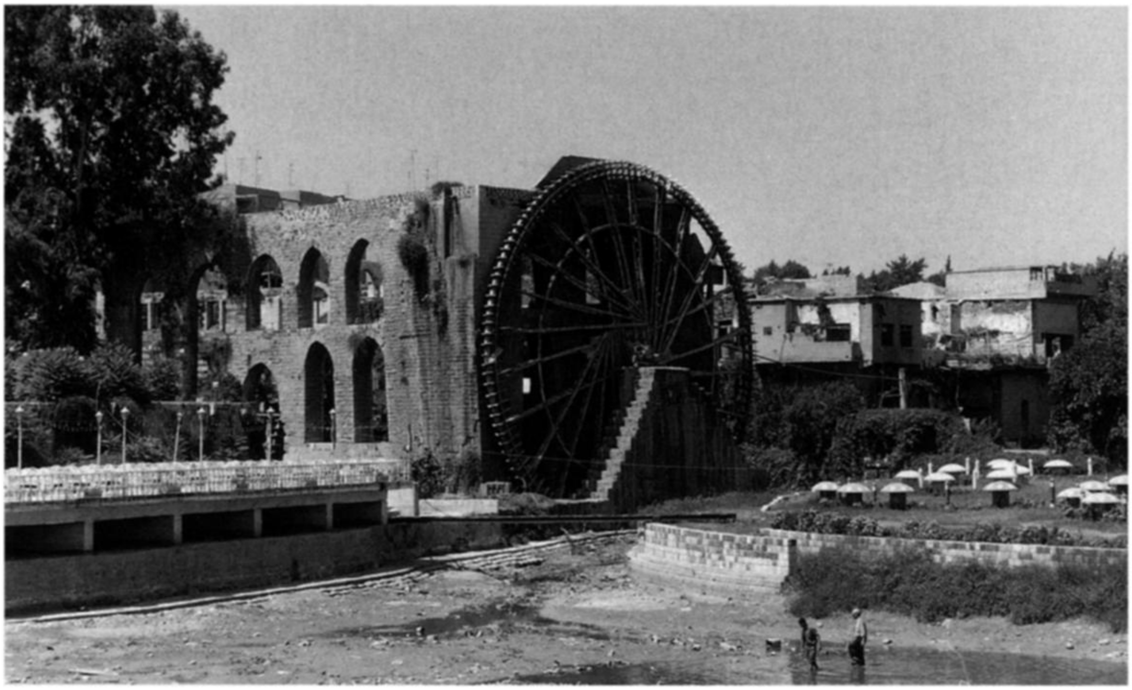


3



4

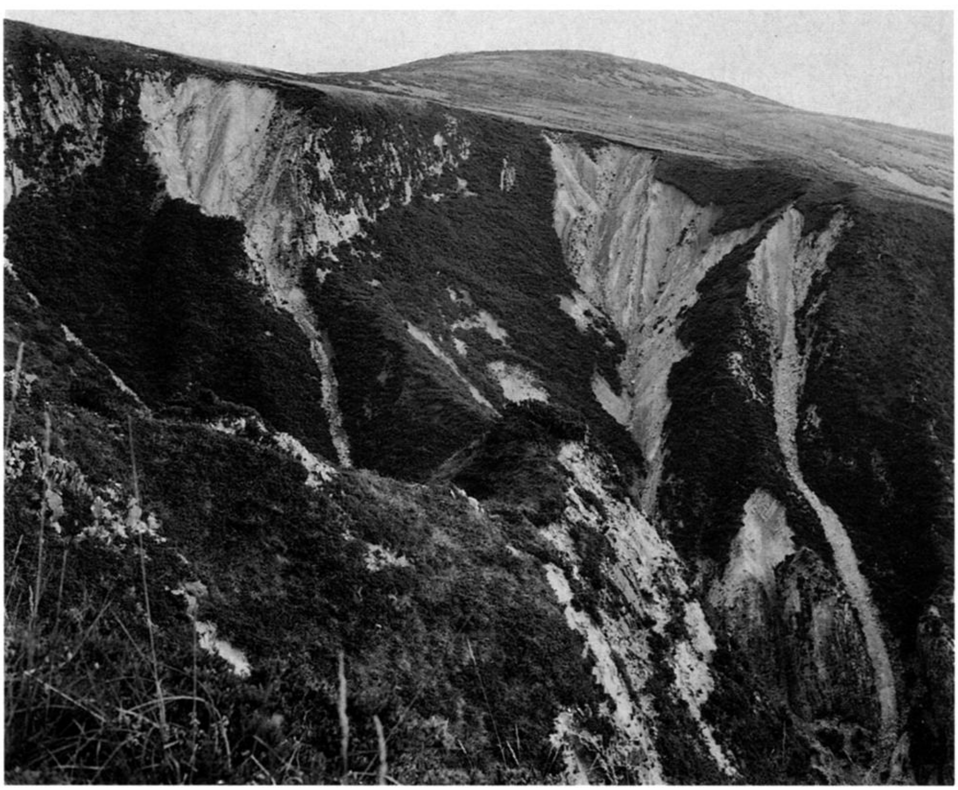
WATER-LIFTING DEVICES. 1. TRADITIONAL SHADUF WELL IN ROMANIA. THE OPERATOR PULLS DOWN ON THE CHAIN TO LOWER THE BUCKET INTO THE WELL, AND THE COUNTERWEIGHTED ARM RAISES THE FULL BUCKET. *Photo: A. Wilson*; 2. *SAQQIYA* (after T. Schiøler, *Roman and Islamic Water-Lifting Wheels* (1973), fig. 5); 3. *NORIA* (after J. P. Oleson, *Greek and Roman Mechanical Water-lifting Devices* (1984), fig. 5); 4. ARCHIMEDES SCREW IN THE ROMAN MINE AT LINARES (after Oleson (1984), fig. 78).



1. *NORIA* AT HAMA ON THE ORONTES IN SYRIA. THIS INSTALLATION GOES BACK TO THE MIDDLE AGES, BUT THE TECHNOLOGY IS LARGELY UNCHANGED FROM THE HELLENISTIC PERIOD. *Photo: A. Wilson*

2. THE SECOND-CENTURY A.D. LARGE WATER-MILL COMPLEX AT BARBEGAL NEAR ARLES. THE AQUEDUCT ENTERING THROUGH THE ROCK-CUT GAP AT THE TOP OF THE RIDGE DIVIDES INTO TWO MILL-RACES, EACH OF WHICH DROVE EIGHT OVERSHOT WHEELS. *Photo: A. Wilson*

1. THE HELIX-TURBINE WATER-MILL COMPLEX AT CHEMTOU, TUNISIA. WATER RUSHING THROUGH EACH OF THE THREE TAPERING MILL CHANNELS ENTERED CIRCULAR WHEEL CHAMBERS TANGENTIALLY AND EXITED THEM AT A LOWER LEVEL, DRIVING SUBMERGED TURBINE WHEELS IN A ROTATING COLUMN OF WATER. THE SPINDLES OF THE WHEELS TURNED MILLSTONES ABOVE THE WHEEL CHAMBERS AT THE LEVEL OF THE CONCRETE PLATFORM. THIS DESIGN ENABLED EFFICIENT EXPLOITATION OF THE RIVER FLOW EVEN WHEN THIS WAS REDUCED IN THE SUMMER. *Photo: A. Wilson*



2. THE SOUTHERN CLIFF OF THE 200-FT DEEP OPENCAST GOLD MINE AT PUERTO DEL PALO, SPAIN. THE ORE OCCURS IN THE QUARTZITE VEINS THAT SHOW WHITE IN THE PICTURE WHERE THEY HAVE BEEN EXPOSED BY HUSHING. THE AQUEDUCT SERVING THE WORKINGS IS FAINTLY VISIBLE AS A LINE ALONG THE FOOT OF THE HILL IN THE BACKGROUND, LEADING TOWARDS A HUSHING TANK PERCHED ON THE EDGE OF THE OPENCAST ABOVE THE RIGHT-HAND HUSH-GULLY.
Photo: Cl. Domergue

AERIAL VIEW OF THE ROMAN GOLD MINES AT LAS OMAÑAS IN NORTHERN SPAIN. THIS PICTURE CONVEYS THE VAST EXTENT OF THE GROUND SLUICING OPERATIONS. AN AQUEDUCT CHANNEL RUNS ALONG THE RIDGE AT THE RIGHT-HAND SIDE OF THE PICTURE (WHITE TRACE) WITH FAN-SHAPED ARRAYS OF GROUND-SLUICING CHANNELS OPENING OFF EACH SIDE OF IT. IN THE FOREGROUND, AN OPENCAST HAS BEEN WORKED OUT. BEHIND THE OPENCAST A BRANCH OFF THE MAIN AQUEDUCT SERVES ANOTHER FAN-SHAPED ARRAY OF GROUND-SLUICING CHANNELS, CONVERGING TOWARDS THE EXIT GULLY IN THE CENTRE OF THE PICTURE. *Photo: Cl. Domergue*