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# THE HISTORY AND PROMISE OF SHALE RESEARCH

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*"Possibly many may think that the deposition and consolidation of fine-grained mud must be a very simple matter, and the results of little interest. However, when carefully studied experimentally it is soon found to be so complex a question, and the results dependent on so many variable conditions, that one might feel inclined to abandon the inquiry, were it not that so much of the history of our rocks appears to be written in this language."*

Henry Clifton Sorby, 1908

Sedimentary rocks are the main repository of information about the geologic past, including the complex interactions between factors that helped to shape ancient continents, such as climate, subsidence, plate movements etc. Popularization of the greenhouse effect and global change has made credible predictions of future changes in climate and sea level a matter of public debate, and has given considerable urgency to the task of understanding how the above factors interact.  Aside from aiding our understanding of driving forces behind climatic changes, such understanding is also of vital interest to those that concern themselves with energy and mineral resources and geologic hazards.  The task before us is obvious, we must find ways to extract all possible information that can be gleaned from the sedimentary record.  Yet, whereas sandstones and carbonates are well enough understood to allow surprisingly lucid deductions about past conditions, fine-grained terrigenous clastics (mudstones, shales), the dominant sedimentary rock type, are still "terra incognita" for most geologists.  Thus, if we are to answer the challenge, the conclusion is inescapable that an improved understanding of mudstones and shales is essential.

Shale and mudstone are both widely used terms for fine-grained terrigenous clastics.  In the more general discussions of this book, however, we will primarily use the term shale, with the understanding that it includes what some prefer to identify as mudstones.

Although there were early and encouraging beginnings in the study of sedimentary rocks (e.g. Sorby, 1908; Cayeux, 1916; Correns, 1938; Boswell, 1961; Milner, 1962), progress has been slow in coming.  Only four decades ago sedimentary geology was still a highly descriptive subject with emphasis on details of rock texture and mineralogy (e.g. Pettijohn, 1957), as well as age and correlation of sedimentary rock units.  A major change took place in the 60's and 70's, when more and more the actual origin of sedimentary rocks became the focal point of inquiry (e.g. Blatt, Middleton, and Murray, 1972), and application of fluid dynamics (Harms et al., 1975), mineralogy (Weaver, 1963; Grim and Güven; 1978), geochemistry (Garrels and Mackenzie, 1971), and mathematical approaches (Krumbein and Graybill, 1965) became increasingly important.  Modern studies of sedimentary rocks are multidisciplinary in nature, emphasizing processes and examination of sediment units in the overall context of sedimentary basins and the array of parameters (such as subsidence, climate, sediment supply, sea level, etc.) that control deposition within them.

Economic aspects of shales are manifold. They are the main source of petroleum and natural gas, and in rare cases they may even act as reservoirs. They supply the raw materials for ceramics, the refractory industry, brick manufacture, and host important economic base metal deposits (Gustavson and Williams, 1981). Mildly metamorphosed mudstones yield roofing slate, a product that is still in demand in North America and Europe (e.g. Wagner, 1991). Aspects of clays in engineering geology are covered by Gillot (1987), and applied clay mineralogy by Grim (1968). Mudstones and shales are also becoming increasingly important as safe repositories for ever increasing quantities of hazardous waste (e.g. Fetter, 1994). Accurately predicting the possible interactions with waste materials and the sealing capacity of a given shale unit will to no small degree hinge on whether we fully understand its origin. Thus, aside from the purely academic interests of shale aficionados, there are sound economic reasons why shales should receive more attention in the future.

Essential as source and seal of hydrocarbons in sedimentary basins, shales and mudstones constitute two thirds of the sedimentary rock record, and contain by far the largest portion of earth history, typically in relatively continuous successions. In light of this, and considering the incentives to better understand the earth's past as well as its future, one would naively expect that this group of sedimentary rocks had been studied extensively in the past decades. A survey of the literature shows, however, that this was not the case (Fig. 1). Probably because sandstones and carbonate rocks contain the bulk of easily recoverable hydrocarbon reserves, there was little economic incentive to study shales during those years when great strides were made in our understanding of sandstones and carbonates. Intellectual curiosity on the other hand is ever present and may mainly be responsible for the steady trickle of shale studies over the decades (Fig. 1).

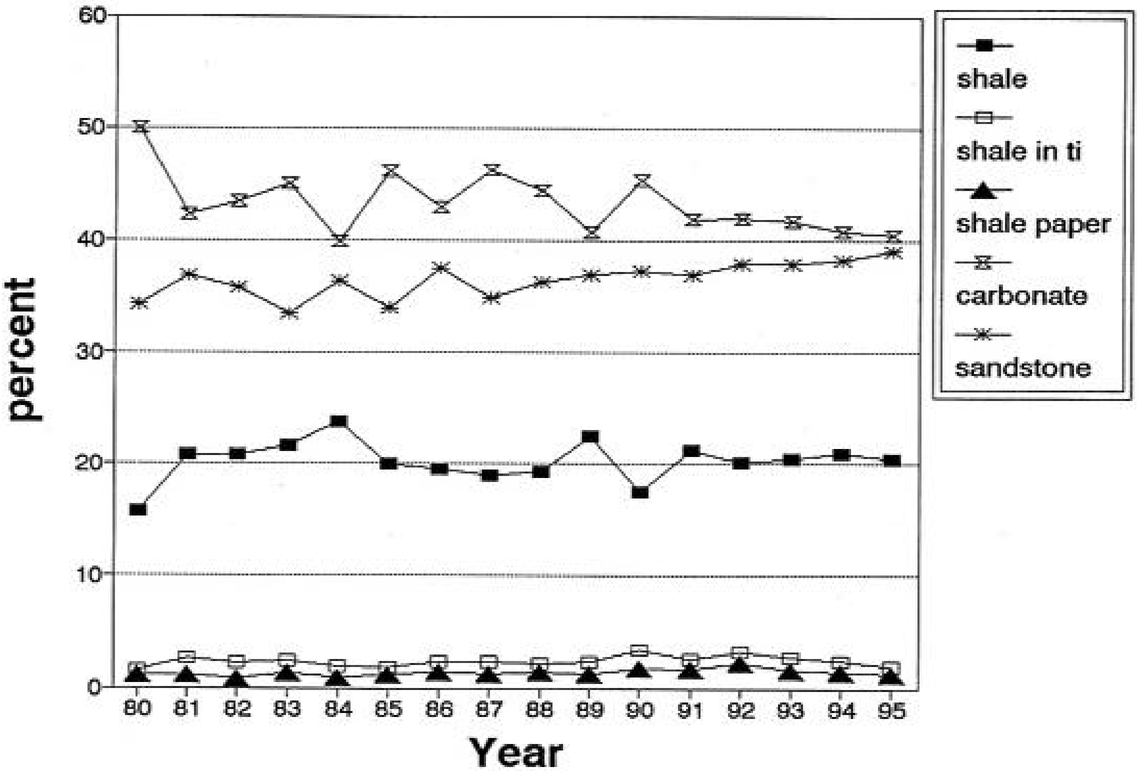


Fig. 1: Results of a search of the GEOREF data base for the years 1980 to 1995. Database was searched for papers that treated sedimentary aspects (such as provenance, facies, environment, depositional processes) of shales/mudstones, sandstones, and carbonates. Figure shows proportions of papers for a given year. The shale/mudstone data were further subdivided into those where shales were discussed to at least some degree in the paper or were mentioned in the title (shale in ti; empty square), and those where shales/mudstones were the focus of the inquiry (shale paper; filled triangle). In actual numbers, there were on average 1332 sandstone and carbonate papers per year, 341 papers where shales were mentioned at all (filled squares), 40 papers that had shale or mudstone in the title (empty squares), but only 22 papers that actually focused on shales/mudstones (filled triangles).

The publication of **Sedimentology of Shale** by Potter et al. (1980) is memorable. It was the first book devoted to questions of shale geology. When the book appeared in print, one of the editors (Jürgen Schieber) eagerly read the first copy he could get his hands on, hoping to find answers to the many questions that he encountered while studying Proterozoic shales for his dissertation. His disappointment was profound. Very few answers, but questions aplenty. Once it had sunk in, however, that this state of affairs was simply the way things were, he realized that there was a "silver lining". Squeezing information from shales was intriguing, and apparently by doing so one could cover a great deal of uncharted territory and enlarge a developing scientific frontier. From then on, **Sedimentology of Shale** became a most frequently perused sourcebook, as well as a collection of numerous fascinating questions, puzzles, and paradoxes. We believe that it is in this capacity that the book had its prevailing impact.

Another important contribution is **Clays, Muds, and Shales** by Weaver (1989). In contrast to Potter at al. (1980), where multiple avenues of inquiry are explored in order to understand the rock record from a sedimentologist's perspective, Weaver emphasizes clay minerals. Their origin, petrography, transport and depositional processes, and their fate during diagenesis are at the heart of the book. It presents an excellent summary of what we understand of modern clay generation and distribution, and in its comprehensive treatment of the clay minerals literature it is probably the best sourcebook for that aspect of shale geology.

Yet, despite the growing interest in shales as signified by publication of books dedicated to the subject (Potter et al., 1980; Weaver, 1989), and despite recent efforts towards careful examination of the shales in the geologic record (e.g. O'Brien and Slatt, 1990; Bennett et al., 1991a; Leithold, 1993, 1994; Wignall, 1989; Zimmerle, 1991; Schieber, 1990; MacQuaker and Gawthorpe, 1993), the study of shales still lags far behind that of sandstones and carbonates (Fig. 1). In too many instances shales are still dismissed as the "interbedded" matrix of more "interesting" lithologies of seemingly greater intellectual interest or economic significance (Potter et al., 1980, p. 3). Thus, to those that are engaged in the study of this least understood type of sedimentary rock, the opening sentiment of this book from Sorby's (1908) classical work on the application of quantitative methods to the study of structures and textures in rocks still rings true almost a century later. The "decade of shales", as anticipated by Blatt (1982), has still not come to pass (Fig. 1). To promote its eventual arrival is the main objective of this book.

There are a number of good reasons why shales should be studied. The most obvious one is of course the fact that the stratigraphic record is so strongly dominated by shales. Also, many shale units contain various proportions of intercalated sandstone and carbonate beds, and sedimentological interpretations of these units are typically biased towards information gathered from these more resistant interbeds. In many instances these interbeds were the result of short-lived high energy sedimentation events, such as storms, floods, or turbidites. The interbedded shales on the other hand are more likely to record background ("normal") conditions (e.g. Potter et al., 1980; Einsele and Seilacher, 1982). Thus, although we have a reasonably good understanding of deposits related to exceptionally high energy events in shale sequences, actual knowledge of parameters and processes that affect deposition under "normal" every day conditions is quite limited. Because the latter are much more likely recorded in shales, intensified study of shales will in the end result in a much improved understanding of the geologic past.

Although sedimentary geologists have pondered cyclic sedimentation for many years now (e.g. Grabau, 1940; Duff et al., 1967), there has been a resurgence of interest with the introduction of sequence stratigraphy (Vail et al., 1977) and subsequent attempts to subdivide the stratigraphic column into a hierarchy of cycles with different duration (see also papers by Bohacs and Schutter in this volume). Whereas there are well established procedures to define 1st through 3rd order cycles via the stratal architecture of sandstones and carbonates within a sequence (Vail et al., 1977), the thin higher order cycles are more elusive. The latter are commonly attributed to astronomical forcing (Milankovitch cycles), and thought to represent the climatic effects of cyclic changes in Earth's orbital parameters (Schwarzacher, 1993). Because of the comparatively complete record of shale successions, they are fertile ground for detailed investigations of these higher order cycles. These may potentially yield new information about underlying mechanisms of climate change and hold the prospect for an improved geological time scale (House, 1985).

Argillaceous background sedimentation in carbonate rocks is a much overlooked subject because its products are difficult to observe and decipher. The large quantities of biogenic components in carbonate rocks camouflage the inconspicuous background sedimentation. Yet, knowledge of composition and provenance of the argillaceous background sediment contributes to our understanding of carbonate sedimentation. In the Upper Cretaceous of Europe the argillaceous background sedimentation has been a long debated subject (e.g. Dorn and Bräutigam, 1959; Harrison et al., 1979; Zimmerle, 1989), and in other carbonate sequences of different ages this problem exists as well (e.g. Hsü and Jenkyns, 1974; Odin et al., 1988).

Studies of modern muds indicate that their sedimentary, chemical, and biological features can be attributed to factors encountered in the continuum associated with transport, deposition, and burial (Bryant, 1991; Bennett et al., 1991b). Thus, through careful study we should be able to filter out features that can, for example, be attributed to climatic conditions, influence of organisms, tectonic setting, etc.. In turn, this should advance our understanding of past changes in ocean and atmospheric circulation, past climates and climate dynamics, as well as shedding some light on the factors that may have been involved in mass extinctions. The search for hydrocarbons and sedimentary mineral deposits will require an ever more detailed knowledge and understanding of sedimentary basins. Drawing on the so far under utilized information locked up in shales may well become indispensable for truly comprehensive basin analysis.

Potter et al. (1980; p. 4) considered four main reasons why the study of shales had lagged behind that of other sediments:

1) the difficulties of imaging and studying single, clay-size particles,

2) the complex diagenetic history of clay particles,

3) lack of experience with recognizing and interpreting “vertical environmental profiles”, and

4) lack of knowledge about paleocurrent systems.

Potter et al. (1980) considered our inability to study the history of single particles as one of the most significant stumbling blocks towards a better understanding of shales. Although the problem of particle resolution and identification has been partly overcome by wide application of the scanning electron microscope (SEM; e.g. O’Brien and Slatt, 1990) there is the remaining puzzle of clay particles that have probably undergone substantial changes during burial and diagenesis. Examining diagenetic changes in shales has received considerable impetus through the application of backscatter (BSE) imaging (e.g. Pye and Krinsley, 1986; Nöltner, 1988; Macquaker and Gawthorpe, 1993), but we still have a long way to go before we can confidently see through the “diagenetic veil”.

Nonetheless, although in the past geologists were indeed greatly hampered by the problem of fine-grained texture and the difficulties of disaggregation, there were a number of outstanding studies that approached the questions posed by shales from various angles (e.g. Rubey, 1931, Richter, 1931; Ruedemann, 1935; Einsele and Mosebach, 1955; Davis and Elliott, 1957; Folk, 1962; Scotford, 1965). Several studies carried out by Harvey Blatt and his students demonstrate simple and elegant approaches to some fundamental questions of shale petrology, provenance, and dispersal (Blatt and Schultz, 1976; Charles and Blatt, 1978; Blatt and Totten, 1981; Blatt and Caprara, 1985).

Through detailed studies of shales it is also becoming obvious that they show systematic vertical successions. Just as in sandstones and carbonates, these can reveal how a diversity of features (e.g. grain size, lamina style, bioturbation, composition) can be interpreted as the product of systematic environmental changes, such as sea level variations (e.g. Macquaker and Gawthorpe, this volume), delta growth (Leithold, 1994), or coastline progradation. There is no doubt that an increase in detailed studies will reveal that such "vertical environmental profiles" are just as common in shales as in other lithologies.

Potter et al. (1980; p. 64) summarized the means of obtaining paleocurrent information from shales. Since then progress has been made in more systematic gathering of paleocurrent data from shale, because current-induced magnetic fabrics produce anisotropy of magnetic susceptibility (AMS method; Schieber and Ellwood, 1988, 1993). This method, however, depends on availability of highly sensitive equipment and the content of magnetic minerals in a given sample. For the latter reason, and because AMS can be produced by other means than current (e.g. deformation), applicability has to be tested in each case. Because there is considerable labor involved for sample collection, preparation, and analysis, whenever alternate paleocurrent information is available, such as aligned fossil material, small starved ripples, etc., it should be utilized to the maximum extent prior to resorting to the AMS method.

With respect to the stratigraphic study of shales, more attention is gradually being paid to stratigraphic breaks, disconformities, and their associated lag deposits (e.g. Conkin et al., 1980). Sequence boundaries in shale sequences tend to be very subtle features, but they are probably much more widespread than currently appreciated. In detailed studies they are increasingly recognized (e.g. Leithold, 1994; Bohacs and Schwalbach, 1992; Bohacs, this volume; Schieber, 1994, this volume), and it will be only a matter of time before sequence stratigraphic analysis will be an integral component in the study of shale successions.

Categorizing shales is by no means a trivial exercise. The various classification schemes in existence (e.g. Ingram, 1953; Dunbar and Rodgers, 1957; Folk, 1965; Picard, 1971; Lewan, 1979; Blatt, Middleton, and Murray; 1980; Lundegard and Samuels, 1980; Potter et al, 1980; p. 14) leave much to be desired, and there is at present no consensus on how to approach this subject. In these classification schemes, compositional variation has been the prime variable used to categorize shales, and not much emphasis has been put on characteristics of texture and fabric. In our experience, most shale sequences exhibit much larger variations in texture and fabric than in composition. For example, shale types shown in papers by Schieber (1989, 1994) would all fall into the mudstone and mudshale fields of Potter et al. (1980, p. 14), yet by using textural and fabric features in addition to composition, it was possible to differentiate 6 shale types in a study of a Proterozoic Shale succession (Schieber, 1989)and as much as 14 in a study of Devonian shales of the Appalachian Basin (Schieber, 1994). Other studies as well (e.g. Nuhfer et al., 1979; Nuhfer, 1980; Cluff, 1980) show that texture and fabric are indispensable for meaningful descriptions and classifications of shales and mudstones. This is analogous to the situation in carbonate rocks, where within narrow compositional confines an incredibly large textural spectrum can be observed.

The textural variability of carbonate rocks was to no small extent made interpretable through the frame of reference provided by the carbonate microfacies concept (e.g. Wilson, 1975; Flügel, 1978). Thin section scale integration of paleontologic, sedimentologic, and petrographic observations as applied for example by Schieber (1989, 1994) to Proterozoic and Devonian shales, is the basis of the microfacies concept (Brown, 1943; Cuvillier, 1952). Although there are substantial differences between carbonate microfacies (essentially monomineralic) and an envisioned shale microfacies (polymineralic), to adapt this approach to shales may in the end lead to the definition of standard shale microfacies types and to generally applicable facies models. Development of a "shale microfacies" scheme may eventually solve our problems with shale classification and should in the end allow sound interpretation of shale environments.

To subdivide this book into chapters was difficult. Because shale research is of an inherently interdisciplinary nature, most contributions touch on a whole range of subjects, rather than confining themselves to a narrow topic. The combination of techniques is highly variable, and the assignment of papers to certain chapters has always an arbitrary element to it. To at least partially overcome this dilemma we have provided a “topical matrix” (Table 1) that shows which topics are discussed in a given paper (marked by black squares and crosses), as well as indicating where the perceived focus of the paper lies (marked by black squares). The central topic of each chapter is introduced and reviewed in an overview at the beginning of the chapter. Most of these are not included in Table 1 because by nature they cover a very wide range of subjects. For the introductions of chapter 6 and 7, however, it seemed to make sense to include the overviews in Table 1 (these are marked with *). We hope that this will help to direct readers to papers that hold special interest for them.

Table 1: Topical matrix for this book. First authors of papers are listed on left side. Papers are arranged in the same sequence as they appear in the book. Topic areas are listed alphabetically along top margin of diagram. Filled squares indicate that the topic is central to the paper or is discussed at some legth, crosses indicate that the topic is discussed in the paper, but that it was not one of the focal areas of the paper. Papers marked with * are chapter introductions. The majority of chapter introductions is not listed here, because they typically touch on a wide range of issues.

| | | age determination | basin analysis | black shale | clay minerals | diagenesis | economic aspects | geochemistry | heavy minerals | metal deposits | microfabrics | microstratigraphy | organic geochemistry | paleoecology | petrography | petrophysics | porosity & compaction | provenance | rare earth elements | sedimentology | sequence stratigraphy | tectonism | trace elements | trace fossils | volcanic input |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Volume I | Potter | | ■ | | | | | | | | | | | | | | | | | | | | | | |
| | Bohacs | | ■ | | | | | | | | | | | | | | | | | | ■ | | | | |
| | Schutter | | ■ | | | | | | | | | | | | | | | | | | ■ | | | | |
| | Ettensohn | | ■ | ■ | | | | | | | | | | | | | | | | | | ■ | | | |
| | Allison | | X | | | | | | | | | | | | X | | | | | ■ | | | | | |
| | Macquaker | | X | | | | | | | | | | | | ■ | | | | | ■ | ■ | | | | |
| | Schieber | | | ■ | | | | | | | | ■ | | | X | | | | | ■ | ■ | | | | |
| | Jaminski | | X | ■ | | | | ■ | | | | ■ | X | | X | | | | | X | | | X | | |
| | Hoffman | | | ■ | | | | X | | | | ■ | X | | X | | | | | | | | ■ | | |
| | Genger | | | ■ | | | | ■ | | | | ■ | X | | X | | | | | | | | ■ | | |
| | Brett | | | | | ■ | | | | | | | | ■ | | | | | | ■ | | | | | |
| | Wetzel | | | | | | | | | | | | | | | | | | | X | | | | ■ | |
| Volume II | Zimmerle | | | | | | | X | X | | | | | | ■ | | | ■ | | | | | X | | ■ |
| | Totten | | | | | | | | ■ | | | | | | X | | | | | | | | X | | |
| | O'Brien | | | | | | | | | | ■ | | | | | | | | | ■ | | | | | |
| | Katsube | | | | | | | | | | | | | | X | ■ | ■ | | | | | | | | |
| | Bloch * | | | | | ■ | | ■ | | | | | | | | | | | | | | | | | |
| | Hutcheon | | | | | ■ | | ■ | | | | | | | | | | | | | | | | | X |
| | Haynes | | | | ■ | | | ■ | | | | | | | | | | | | | | | | | ■ |
| | Melson | | | | ■ | | | ■ | | | | | | | | | | | | | | | | | X |
| | Grathoff | ■ | | | ■ | ■ | | X | | | | | | | | | | | | | | | | | |
| | Mahoney | | | | | | | ■ | | | | | | | | | | ■ | X | | | | ■ | | X |
| | Sethi | | | | | | | ■ | | | | | | | | | | ■ | ■ | | | | X | | |
| | Hannigan | | | X | | X | | ■ | | | | | X | | | | | X | ■ | | | | X | | |
| | Sethi-Schieber * | | | X | ■ | | ■ | | | ■ | | | | | | | | | | | | | | | |
| | Leventhal | | | ■ | | | ■ | ■ | | ■ | | | X | | | | | | | | | | X | | |

In the first volume of this book, chapter one, stratigraphy and basin analysis, contains papers that address the “bigger picture” and give some examples on how sequence stratigraphic approaches might profitably be employed in shale studies. Chapter 2, deposition of mudstones and shales, is a collection of papers that on various scales concentrate on depositional processes and features of both modern and ancient muds, although some papers also contain substantial portions that are the focus of chapter 1. The third chapter consists of reviews of the paleoecology of body and trace fossils. These should be very helpful for those that had little or no prior exposure to paleontological approaches in shale and mudstone studies.

The second volume of this book contains papers that report on a variety of laboratory investigations of mudstones.  Chapter 1, petrography, contains papers that emphasize petrographic approaches in the study of shale sequences.  The third paper in this chapter (O'Brien et al.) has been placed here because of the illustration of SEM techniques, otherwise it could have just as well been placed into chapter 2 of volume 1.  Chapter 2, petrophysical observations, is a review by Katsube and Williams of the effects of burial history on porosity, permeability, and fabric.  Chapter 3 contains a collection of papers that deal with a wide range of geochemical approaches to shale studies.  Included are provenance studies, investigations of diagenetic remobilization of elements, the question of potassium enrichment in shales, modeling of water-rock interactions during burial and diagenesis, and the problem of differentiating detrital and diagenetic clay minerals.  The overview by John Bloch sets the tone by pointing out the many gaps in our understanding.  Finally, chapter 4 consists of a review of the many economic aspects of shales, including raw materials and derived products, and an in depth review of metal enrichment in black shales by Leventhal.

# FIGURES

**Figure 1:** Results of a search of the GEOREF data base for the years 1980 to 1995. Database was searched for papers that treated sedimentary aspects (such as provenance, facies, environment, depositional processes) of shales/mudstones, sandstones, and carbonates. Figure shows proportions of papers for a given year. The shale/mudstone data were further subdivided into those where shales were discussed to at least some degree in the paper or were mentioned in the title (shale in ti; empty square), and those where shales/mudstones were the focus of the inquiry (shale paper; filled triangle). In actual numbers, there were on average 1332 sandstone and carbonate papers per year, 341 papers where shales were mentioned at all (filled squares), 40 papers that had shale or mudstone in the title (empty squares), but only 22 papers that actually focused on shales/mudstones (filled triangles).

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