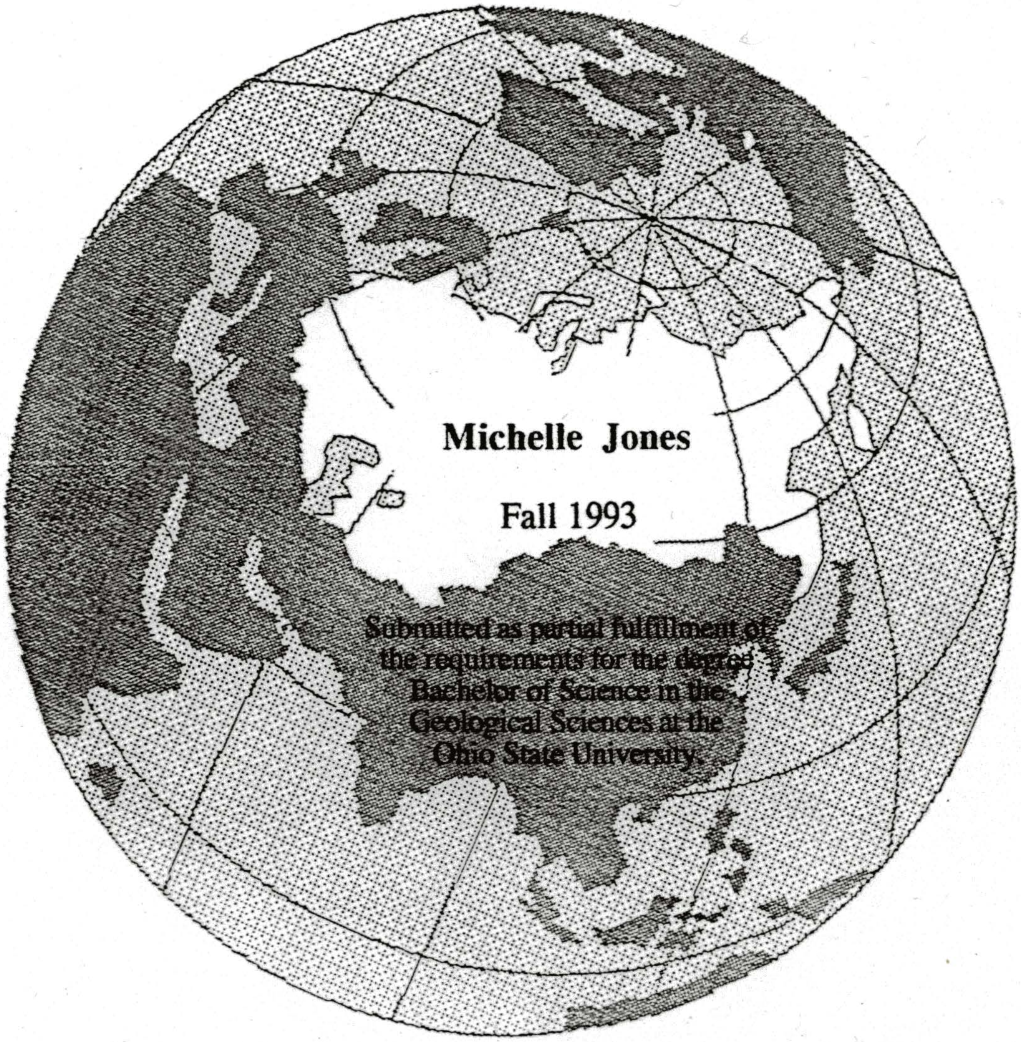
Senior Thesis

Stratigraphic Method of Eustatic Quantifications; a Sea Level Curve Based on Jurassic-Cretaceous Strata of the Russian Platform



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ABSTRACT

Two types of sea level are presently defined: relative and eustatic. Relative sea level (RSL) is the sea surface elevation relative to some local land surface. Eustatic sea level (ESL) is a term used to characterize worldwide changes in sea level, and reflects the relationship between the volume of the ocean basins and the volume of ocean water. In order to measure eustatic changes with respect to the lithosphere a reference frame is necessary. The most reasonable reference frame is a stable platform, free from local epeirogeny and subsidence. The broad stability of the Russian Platform makes this area an ideal reference frame for calculating ESL from the Late Jurassic to the Paleogene. Information about sea level fluctuations can be derived from stratigraphy through a technique known as backstripping. The backstripping equation relates eustasy to sediment thickness, water depth, and tectonics. This method restores the strata to the original state of deposition, before compaction loading, and epeirogeny. On the basis of widespread horizontal uniform thinly bedded Mesozoic marine strata, the Russian Platform is inferred to be tectontonically stable. The backstripping method applied to the Russian Platform restores the stratigraphy to the original elevation of deposition, and because the Russian Platform has not experienced subsidence or uplift, the resulting RSL curve is also applicable as a ESL curve. Subsidence rates for surrounding basins forming during the same time can be determined using the quantified eustatic sea level curve. Subtracting the eustatic sea level curve from the calculated relative sea level of the subsiding basin will result in the amount of subsidence. This procedure has been applied to the Caspian Basin resulting in a subsidence rate of 7.8 m/m.y. from the mid-Callovian to mid-Aptian.

Introduction

The area of past sea level research has been gaining large notoriety over the past couple of decades stemming from oil exploration, and the relation of sea level to sequence stratigraphy. However, there are basic problems which have impeded quantification of sea level variations. Conflict is emanated from a lack of understanding and definition of the term "sea level." Complications also arise with properly choosing an accessible point on the Earth's surface to use as a reference frame for gauging past increases or decreases of water levels. Until researchers unite to come to some agreement these logistical problems will probably continue to cause confusion and debate.

In order to proceed with a discussion about sea level, clarification must be made of some basic concepts. First, there must be a clear understanding of the difference between relative and eustatic sea level. Relative and eustatic are the two types currently defined. *Relative* sea level (RSL) is the sea surface elevation relative to some local land surface. Since land surfaces periodically experience subsidence and uplift at different rates, comparisons between two areas will not furnish the same magnitude of change, and thus can not be used to generalize global sea level. *Eustatic* sea level (ESL) is a term used to characterize worldwide changes in sea level. An appropriate way to determine eustatic sea level is to compare the volume of the world's ocean basins to the volume of the world's water (*Fairbridge*, 1983; *Sahagian & Holland*, 1991; *Sahagian and Watts*, 1991; *Sahagian and Jones*, 1993). Increasing the amount of ocean water results in increasing the global sea level. Increasing the volume of ocean basin will have an opposite effect by decreasing the global sea level. The magnitude of sea level rises and falls indicated on a eustatic sea level curve reflect these volume changes and give evidence for known and perhaps unknown major tectonic or climatic events. It is important to analyze the methodology used to determine past sea levels in order to determine if the results are indicating eustatic or relative sea level.

A second area of complication which must be clarified, is the choice of a frame of reference that would adequately gauge a change of eustatic sea level. Applying seismic (and now sequence) stratigraphy to thick sequences from passive margins is a method most commonly utilized for determining sea level (*Haq et al*, 1987; *Christie-Blick*, 1990; *Vail et al*, 1984; *Hardenbol et al*, 1981). This method results in sea level being variable with respect to the passive margin reference frame, plus the reference frame experiences variation resulting from differing rates of subsidence. Therefore, the subsidence taking place at passive margins must be subtracted out from stratigraphic data. However, the uncertainty inherent in estimation of long-term subsidence is greater then the magnitude of sea level change, so passive margins are a poor choice of a reference frame for measuring long-term eustatic sea level. However, the thick continuous sequences found on passive margins are good for measuring the relative sea level (Sahagian and Jones, 1993). Another method is to use oceanic islands like a "dipstick". This practice is only good for short term sea levels because the oceanic lithosphere is experiencing subsidence (*Sahagian and Watts*, 1991).

An ideal frame of reference is the center of the earth, but its inaccessibility makes this method impossible (*Sahagian and Watts*, 1991). The most reasonable reference frame is a stable area in the continental interiors where ocean waters have deposited sediment, and animal or plant remains are preserved in the rock record. The area must also be free from tectonic activity and subsidence during the time of deposition in order that eustasy is the only factor influencing the stratigraphy (*Sahagian & Holland*, 1991; *Sahagian and Watts*, 1991). At the present time there are few known areas in the continental interiors identified as a stable platforms which would be an ideal reference frame to use for determining eustatic sea level. A large area in North America, around Minnesota, has been referred to as a stable platform (*Merewether*, 1983; *Sahagian*, 1987; *Sleep*, 1976; *Sloan*, 1964). There is also a broader stable area in Russia which has been described as more reliable for use as a reference frame (*Sahagian*, 1989). The stable region includes much of what is commonly referred to as the Russian Platform. Since this area has remained stable, only sea level and continental isostasy are variable. Thus, a quantified relative sea level curve obtained by backstripping Russian Platform sediments results in a quantified eustatic sea level curve. The Russian Platform and other tectonically defined regions are denoted on the map in figure 1. The Russian Platform is denoted by an M followed by a number. Penza is indicated by a P, Caspian depression by a C, and western Siberia by a S.

The degree of relative sea level changes varies over a wide range of time scales and with geological settings. Therefore, it is necessary to categorize fluctuations depending on the time frame occupied, magnitude of sea level change, and geologic or climatic conditions present to cause such changes. Sea level changes have been classified into three different divisions: short term, medium term, and long term (*Smith and Dawson*, 1983, p. 4). Small magnitude of changes are observed on a scale of seconds to days, such as, seiches, wind driven waves, and storm surges (*Emery and Aubrey*, 1991). Other changes can take place over a matter of a day to years, for example, diurnal tides, tsunamis, floods, and near shore waves. In addition, human agricultural and manufacturing habits over many years have shown to affect the relative sea level. These examples of small magnitude sea level change are on the order of what Smith and Dawson (1983) entitle short-term framework. These variations are usually restricted to local scales. The medium-term framework is on the order of 10^3 to 10^6 years. These global changes of sea level are mostly due to glacial and interglacial cycles (*Smith and Dawson*, 1983; *Emery and Albrey*, 1991). The long-term framework are sea level changes over $>10^7$ years ago. Tectonic cycles, isostatic responses, and rifting along continental margins or of the mid-oceanic ridge are the causes of such fluctuations of sea level, and are detected on a global scale.

Backstripping

A sea level curve can be constructed by determining the present elevation of sediments, and then making the deduction this elevation is reflective of the minimum sea level, provided consideration is made for changes in the sediments' position with respect to original sea level. This adjustment stems from isostatic responses of the lithosphere to sediment load, and compaction of sediments in each unit. The backstripping equation has been developed to relate the present characteristics of sediments to the original state by correcting for isostasy and compaction. The equation computes the elevation of sediment above present sea level by removing each unit at a time, decompacting underlying units, and then adjusting for the isostatic response due to the decreased sediment load. Adjusting for the isostatic response requires unloading the stratigraphic units from the basement using either the Airy or flexural models (*Watts*, 1988). Once this has been done, the addition of local water depth results in the calculated relative sea level. Since the stable Russian Platform is our chosen frame of reference, the local relative sea level curve is defined as eustatic. The following is a discussion as to the influence of isostatic adjustment, compaction, and how each is incorporated into the final backstripping equation.

Isostatic adjustment

The isostatic response of the continent resulting from an increase in sediment load can be calculated using the Airy model or the flexural model (*Turcotte et al.*, 1982). G. B. Airy (1855) used geodetic surveying to support his hypothesis crustal thickness is thicker below mountainous areas as compared to the thickness of lowlands (*Watts and Daly*, 1981). The *Airy* model assumes the crust can not support an additional increase in load and thus responds by subsiding uniformly (Fig. 2)(*Watts*, 1981; *Steckler and Watts*, 1982; *Turcotte et al*., 1982). It is important to note, first, when using the Airy model the increase in the weight of the overburden is only compensated in the local area. Secondly, the Airy model assumes the crustal column is overlying a weak fluid (*Watts and Ryan*, 1976). The crustal roots response to this increase in the overburden is determined by (*Watts and Ryan*, 1976; *Turcotte and Schubert*, 1982, p. 225):

$$b = \left\{(\rho_c - \rho_w) / (\rho_m - \rho_c)\right\} \qquad \text{(eq. 1)}$$

where h = elevation above sea level

b = thickness of crustal root.

ρ_c = density of crust.

ρ_m = density of mantle.

ρ_w = density of water.

The Airy model was considered appropriate (as compared to the flexural model) for this study because the Russian Platform is such a broad area with uniform sedimentation. The stable platform contains units with relatively constant thicknesses over a greater area then the lithospheric flexural wavelength, resulting in the Airy isostatic response to lithospheric loading to be maintained (*Watts and Daly*, 1981; *Sahagian and Holland*, 1991).

The *flexure* model assumes a portion of the increase in density can be supported by the lithosphere, plus supported by buoyancy (*Watts*, 1981; *Steckler and Watts*, 1982). The model also postulates the lithosphere is rigid and unfaulted. This allows the increase in overburden to be distributed horizontally and supported by the shear strength (*Watts and Ryan*, 1976).

Porosity

If compaction was not a factor in determining sea level, then it would be possible to assume the present elevation of the sediment was the elevation upon deposition, and would thus reflect the minimum sea level. Of course, this is not possible because the thickness of units are decreased over time due to the increase in the weight of overburden. Pressure increases with depth forcing more fluid out of pore spaces resulting in decrease of porosity with greater depths. The porosity also varies with different lithologies (*Athy*, 1930). Since the stratigraphy on the Russian Platform contains an assortment of sediment types, differences of porosities are also factors which the backstripping equation must take into account. Changes in porosity due to depth is determined by (*Angevine, Heller, and Paola*, 1990, p. 12; *Sclater and Christie*, 1980):

$$\phi_N = \phi_0 \exp(-c\ z) \qquad \text{(eq. 2)}$$

where ϕ_N = current porosity.

ϕ_0 = porosity when originally deposited.

c = decompaction constant for each lithology.

z = present depth of burial.

For matters of simplicity, the calculations made using the backstripping equation only considers the difference in porosity of limestone, sandstone, and shales. Each value used for the different lithologies are give in figure 3.

Backstripping Equation

Analysis of the strata for the purpose of backstripping involves determining the thickness, water depth, and, lithology. Sediment thickness is influenced by tectonic uplift or subsidence, water depth, and lithology. The tectonic activity of an area can be extremely influential on the sediments thickness. Large thickness of strata due to tectonics can be found in areas such as passive margins and deep sea sediment. Small thickness of strata are characteristically confined to stable areas of a continental interior where ocean waters have accessed. Tectonic activity must be subtracted out of any relative sea level curve, which requires knowledge of the rate of uplift or subsidence rate. Determination of uplift or subsidence rates can be difficult and once accomplished presents a margin of error greater then the magnitude of inferred eustatic variations. One approach to solving this problem is to decide on an area of study which is stable, in order that tectonic movements do not introduce large errors into the sea level curve constructed by backstripping. This is the reasoning behind choosing the Russian Platform as the reference frame.

To use the backstripping equation to restore the sediment back to its original position prior to decompaction, the additional weight resulting from the overlying water must be considered. Unfortunately, determining water depth can prove to be a difficult task, particularly for deep water. Determining water depth is made easier by analyzing sediments deposited in a shallow water environment (*Watts*, 1981). Certain benthonic fossils and near shore sedimentary structures normally found in a shallow water environment help to determine the water depth, where in a deep water environment there is less evidence to aid in evaluating the water depth. The water depths maintained on the stable Russian Platform during the Jurassic and Cretaceous generally range from 2m to 25m. Fossils have been found to be abundant in these relatively shallow environments on the platform thus aided dating methods.

When backstripping it is important to differentiate the difference in sediments or rock types because the amount of decompaction will vary with changes in the lithologies. Determining the decompaction of sediment requires the knowledge of its porosity. As explained above, the porosity has been simplified to only three lithologies, thus, the consideration of decompaction has been simplified to the same three lithology types: limestone, sandstone, and shale.

The backstripping equation relates eustasy to sediment thickness, lithology, water depth, and tectonic subsidence. The backstripping equation is as follows (*Steckler and Watts*, 1978; *Watts and Steckler*, 1979; *Angevine, Heller, and Paola,* 1990):

$$T = \Phi\{[\ S^*(\rho_m-\rho_s)/(\rho_m-\rho_w)] - \Delta SL[\rho_w/(\rho_m-\rho_w)]\} + \Delta Wd - \Delta SL \qquad \text{(eq. 3)}$$

where

T= thermo-tectonic subsidence (water loaded) during some time interval.

S^* = sediment thickness deposited during time interval prior to compaction.

ρ_s = mean density of sediment.

ρ_s = mean density of mantle.

ρ_w = mean density of water.

ΔWd = change in water depth during time interval.

ΔSL = eustatic sea level rise during time interval (may be positive or negative).

$\Phi = 1/(1+C)$ = basement response function for flexural backstripping (*Watts et al*., 1982).

$C=Dk^4/(\rho m-\rho w)$, and k is the flexural wave number

The value for the mean sediment density is determined by the following equation (*Steckler and Watts*, 1978; *Angevine, Heller, and Paola*, 1990):

$$\rho_S = \frac{\sum_{1}^{i} \left| \phi_i \, \rho_W + (1 - \phi_i) \, \rho_g \right| T_i}{S^*} \qquad \text{(eq. 4)}$$

where T_i = thickness of the sediment

ρ_g = density of the grain

ρ_s = density of the sediment

ρ_w = density of water

ϕ = porosity of the sediment

S^* = Sediment thickness prior to compaction ($S^* = \Sigma T_i^*$)

In order to solve the backstripping equation for eustatic sea level rise (ΔSL), only data for three variables must be provided: density of sediment (ρ_{s}), water depth (ΔWd), thickness (S^*). The three remaining variables have been determined from outcrop observations, published literature (*Oponiye*, 1962; *Zakharov*, 1986, 1989b; *Bogomolov*, 1990; *Lebedeva*, 1991,), and well descriptions. Of course, there is potential for some error in the data which has been illustrated graphically for the individual wells sea level curve in figure 4. The most significant error is the water depth estimate. The error is smaller and more accurate for a shallow water environment. It has been estimated that a near shore facies with a water depth of 2 m has an error estimate of +2 m; transitional environment has a water depth of 10 + 5 m; and for an offshore environment has a water depth of 25 + 10 m (Table 1). These errors have been considered and incorporated into the final sea level curve, resulting in final eustatic sea level curve as two bands rather then one continuous line (Fig. 4).

Stratigraphic Analysis

The former Soviet Union rests on a broad continental land mass constructed from a wide variety of geological processes. The strata composing much of the Russian Platform range in age from the Middle Jurassic to the late Paleocene (30 - 166 m.y). Most of the individual beds are bound both above and below by unconformities, indicating no subsidence during time of deposition. A stratigraphic column constructed from the data in appendix II is provided in figure 5 in order to illustrate the large amount of unconformities and the thinness of the beds. These unconformities can be attributed to either erosional or non depositional processes. The distinction between the two is not important and is not pertinent to the construction of the sea level curve. Thin beds and unconformities are not so prevalent in the Caspian or western Siberian Basin stratigraphy, indicating subsidence was taking place in these areas but absent from the Russian Platform.

On the basis of widespread horizontal uniform thinly bedded Mesozoic marine strata, much of the Russian Platform is inferred to be tectontonically stable. Fringes of the platform experienced some downwarping inflicted by the surrounding Caspian Basin and the Dneiper-Donets Basin. The stable Russian Platform is denoted by green, Penza by yellow, and Caspian Basin by red, in figure 6. Penza is a tectonic region which experienced greater amounts of drawdown from the Caspian Basin.

The biostratigraphic analysis is based primarily on ammonites, bivalves, forams, and palynomorphs (*Gerasimov*, 1962, 1969; *Rotenfel'd*, 1965, *Krymgoltz*, 1972). However, with such a wide range of index fossils, biostratigraphic resolution of Russian strata is restricted to stage level during particular times. For example, the Upper Hauterivian is divided into 4 units(denoted as 1-4), but the Lower Hauterivian has not been divided into units. Ability to use biostratigraphy as a determinate for stage and substage levels varies depending on locality. Absence of biostratigraphic zones enable distinction of non visible unconformities. Each stage is discussed in the follow section beginning with the older strata and proceeding to younger.

Bathonian

Much of the Bathonian observed on the Russian Platform is represented by relatively deep water shales (estimated water depth of 25 m). Preserved sediments of Bathonian age are limited to only four of the analyzed wells on the Russian Platform, and of these four, two are located on the southeastern fringe (M19 and M1001)(Fig 6). Bathonian sediment from these two wells are relatively thick, ranging from 30 m to 43 m. Due to these large thicknesses and absence of deposits over much of the remaining platform gives cause for speculation. It is possible that downwarping on the fringe of the platform resulted from the adjacent subsiding Caspian depression, thus producing large thickness.

The two other wells are located on the northern portion of the Russian Platform. Therefore, sea level must have been high enough to transgress over the entire platform depositing sediment at least 3.0 to 5.5 m thick. Wells containing thick sequences of deep water sand and shale are present in the Penza and Caspian region of Lower and Middle Bathonian.

Callovian

It has become clear, after comparing time scales and biozones between Russian and American publications, there is a conflict as to where the boundary of the Middle and Upper Jurassic should be placed. Russian geologists place the boundary at the bottom of the Callovian stage. In contrast, the International Subcommission on Jurassic Stratigraphy (IVGS Commission on Stratigraphy) determined the Middle/Upper boundary to be located above the Callovian stage. Geologist globally, excluding the Russians, have accepted the IVGS Commission on Stratigraphy ruling and place the boundary at the base of the Oxfordian (*Westermann*, 1988). Much of the information gained about the stratigraphy and geology of Russia was obtained from the Russian literature. Therefore, for convenience any reference made to the Middle/Upper Jurassic boundary coincides with the Russian authors.

Deposits of Callovian are found over a broad area on the Russian Platform. The Lower Callovian displays silts with pyrite, marl, phosphorite nodules, and fine sands (*Meledina*, 1988, p. 34). This same lithology was observed in outcrops during a exploration of the platform. Sediment thicknesses do not exceed 16.5 meters. The transition to deposits of silts and fine sands indicates a general regression off of the Russian Platform. The Middle Callovian is bound both above and below by unconformities. No deposition took place during the end of the Lower Callovian and into the Middle Callovian. This is considered a period of erosion. Deposition continued during the Upper Callovian beginning with oolites and fining upward to deep water shales.

Oxfordian

There is an abundance of wells on the Russian Platform containing strata of Oxfordian age, dispersed throughout northern and southern areas. Wells which lacked sediment of Oxfordian age are located in the northwestern corner of the Russian Platform (wells M9, M13, M307, and M331)(Fig 6). It is possible that absence of data in this localized area is a result of an erosional event. Lower and Middle Oxfordian was observed by Dr. Sahagian in outcrops to be composed mostly of black shales. However, there has also been observations of marl in various other locations (*Mesezhnikov*, 1988, p. 41). Upper Oxfordian has been observed to be a fissile black shale only partially lithofied. Mesezhnikov (1988) states this upper unit consists of black and dark gray clay 2 to 7 m thick which is consistent with what we examined.

Samples were obtained from exposed units of Middle and Upper Oxfordian for further analysis. Middle Oxfordian showed an abundance of preserved palynomorphs of monoclopate (with a single colpus) and bisaccate (with two vesicles) pollen, and monolete and trilete spores. Upper Oxfordian palynologic examination revealed a moderate presence of well preserved palynomorphs. Types of palynomorphs included are monocolpate pollen, bisaccate pollen, trilete spores, and dinoflagellates, *Impletosphaeridium*, and *Batiacasphaera* (Appendix II).

Kimmeridgian

In the wells containing both Oxfordian and Kimmeridgian there is a continuation of shales deposited with no recognizable unconformity between the two stages. Unlike the wide spread distribution of Oxfordian shale, the Kimmeridgian is mainly restricted to the northern portion of the Russian Platform. The absence of deposited sediment in the southern area of the Russian Platform can be attributed to a large erosional event during the Lower Volgian, which continued down through the Kimmeridgian. There are also thin interbedded layers of phosphorite nodules, restricted mostly to the upper substage (*Mesezhnikov*, 1988, p. 47).

Volgian

The Lower Volgian is not present in any of the analyzed wells and outcrops on the Russian Platform or in the Penza regions. Only well C31 shows 80 m of shale and medium grained sands. The absence of sediment for the Lower Volgian is due to a large erosional event prior to the Middle Volgian, which extended down through the Kimmeridgian in the southern area of the Russian Platform. All the wells containing deposits of Middle Volgian are confined both above and below by unconformities. The lithology of the Middle Volgian deposits are medium to coarse sands. The coarse sands contain phosphorite which can be attributed to the animal remains or chemically precipitated out from the sea water. Thickness of the sands on the Russian Platform range from .8 meters to 5.4 m. This stage has been divided into two subunits. The lower unit of the Upper Volgian is characterized by shale with phosphorite, consisting of ammonites and belemnites. The upper unit consists of fine white sand containing a wide variety of fossils and plant remains, such as, ammonites, bivalves, gastropods and flora. A sample from this upper unit was obtained during Dr. Sahagian's exploration of the stable region. The grains are observed to be unconsolidated, rounded, and well sorted.

Berriasian

Few wells contain deposits of Berriasian age. Of the few wells where Berriasian is present, the lithology consist of thin layers of medium and course sand. The wells on the Russian Platform reveal strata that are bound above and below by unconformities. A well in the Penza region also has Berriasian age deposits (P17)(Fig. 6). Thickness of only 1.4 m and is a medium sand. Contrary to the Russian Platform strata, this well in the Penza region only has an unconformity above the strata. The strata rests conformable on the Upper Volgian. The S100 well in the Siberian region displays sediment of Berriasian age. This is an extremely thick layer of shale, deposited at a water depth estimated to be 200 m. An abundance of forams have been found within the shale.

A specimen of Lower Berriasian was obtained from the platform and included in the palynological analysis. Abundant palynomorphs were observed in the sample consisting of trilete spores, *Corollina*, bisaccate pollen, and dinoflagellates, *Hystrichosphaeridium, Aldorfia, Circulodinium, and Muderongia* (Appendix II).

Valanginian

There are no analyzed wells on the Russian Platform with preserved deposits of Valanginian. Nalivkin (1973) summarizes the Valanginian lithology of the U.S.S.R., drawing from numerous other published literature. Each cited author confirms our observation of Valanginian absence from the Russian Platform (*Lyutkevich*, 1959; *Sazonov*, 1957). In the Penza region Sazonov (1957), Beznosov et al. (1978), and Sahagian and Jones (1993) have observed small thicknesses ranging from 1.5 to .2 m of glauconitic sands with phosphorites. Beznosov et al (1978) goes on further to state the presence of ammonites, belemnites and pelecypods at the base.

Examination of the data obtained from the wells indicated in figure 6 show a majority of the deposits are restricted to the Penza region. These are characterized by small thicknesses of mediums sands, ranging from .6 to 5.0 meters. The Caspian and Siberian regions also have deposits of the Valanginian. Water depth for Penza and Caspian regions are estimated to be 2 m. For the Siberian wells the water depth is inferred to be greater, estimated to be between 100 and 150 m.

Hauterivian

Wells containing Hauterivian age sediment are abundant on the Russian Platform, Penza, and Caspian regions. Large amount of deposition during this stage occurred all across the regions, thus, the Hauterivian was divided into two substages. The Upper Hauterivian has 4 further subdivisions, denoted by a 1, 2, 3 or 4. Of these 4 subdivisions, Upper Hauterivian 1 and 2 are missing from the Russian platform due to perhaps low sea level or erosion. Unconformities are at the base of the lower, middle, and upper substages. During the Lower Hauterivian, on the Russian Platform, medium grained sands had been deposited in a shallow environment, with a water depth of 2 m. An outcrop sample of the Lower Hauterivian unit has been obtained for palynologic analysis. Examination revealed poor preservation of palynomorphs, fragmented spores, bisaccate pollen, monoclopate pollen, and dinoflagellate fragments (Appendix II). The lithology changes from the medium sands on the Russian Platform, to a shale in the Caspian region. Along with the lithology change from the Russian Platform to the Caspian region, the water depth increased from 2 m to 10 m. The Hauterivian 3-4 exhibits a fining upward to shale. This is interpreted to be deposited as a result of a major transgressive event. Upper Hauterivian 4 (25 m water depth), as compared to Upper Hauterivian 3 (10 m water depth), is a deeper water shale beginning with silt at the base.

Barremian

Barremian age sediments are distributed widely across the Russian Platform, Penza , Caspian, and are also present in western Siberia. From the Caspian to the Russian Platform the lithology indicates a coarsening to the northwest. Lower and Upper Barremian are present in the regions, with an unconformity between the two substages. Lower Barremian lithology is mostly shale while the Upper Barremian is characterized by silts and fine sands.

Aptian

There is an abundance of wells on the Russian Platform with Lower Aptian sediments. The Lower Aptian has been divided into two subunits, labeled lower Aptian 1 and 2. The first subunit is older in age compared to the second subunit. Lower Aptian 1 is composed mostly of silt at the base and then grading into a medium sand which continues into the second subunit. No unconformity is present between the two subunits. Over this time period there was an increase in the sedimentation rate producing a thick sequence of sediment, ranging in thicknesses of 15 to 50m.

A clear unconformity exista between the Lower and Upper Aptian. Upper Aptian disappears off of the Russian Platform, with deposits only present in two wells both in the Penza and Caspian regions. Water depth decreases from the Caspian Basin to the Russian Platform in a north-west direction from 25 m to 2 m respectively.

Albian

The continual absence of deposits on the Russian Platform continues from the Upper Aptian to the Lower Albian. Where sediments are observed the lithologies are deep water shales and silts. This indicates that absence of sediments in many of the adjacent wells is the result of an erosional event. During Middle Albian the water depth on the Russian Platform was 2 m but Penza had a water depth of 10 m. A rather large transgression occurred from middle to Upper Albian. Water depth over this time period on the Russian Platform increased from 2 m to 25 m. Water depth in the Penza region increased from 10 m to 33 m.

Cenomanian

Few wells in all regions contain sediments of Cenomanian age. Lower Cenomanian is present in only two wells on the Russian Platform, consisting of fine and medium sands. Water depth for these two wells on the Russian Platform has been estimated to be 2 m increasing to 10 m in the Caspian region. Upper Cenomanian is not preserved in any of the wells.

Turonian

The Lower Turonian is only preserved in one well which is represented by a marl. The presence of marl indicates a relatively deep water environment. The absence of such lithology in adjacent areas has been interpreted to have resulted from a large Coniacian erosional event extending down through the Turonian to the Upper Cenomanian and in some areas down to the Lower Cenomanian.

Coniacian

As discussed above, the Coniacian is missing from the Russian Platform resulting from an extensive erosional event. Thick sequences of 20 m to 28 m are preserved in the Caspian region.

Santonian

In wells containing both Coniacian and Santonian sediments, there is no evidence of unconformities. A transgression event took place during the Santonian resulting in water depth to increase from 2 to 25 m. The deeper water lithology consists of medium grained sandstone with silicate cement, and belemnites at the base.

Procedure

The procedure for constructing the sea level curve has been simplified diagrammatically using a flow chart (Fig. 7). The flow chart illustrates the procedure in an easy to follow step by step progression and also provides a good frame work for developing an outline to a discussion. Thus, the highlighted points on the procedural flow chart will be followed closely in the succeeding sections. The procedures involve first compiling the stratigraphic data, then imputing the data into the backstripping equation, and then graphing the results, producing a sea level curve. The following sections discusses each of these components in more detail.

Compile Stratigraphic Data

Much of the necessary stratigraphic data was already available in the Basin Analysis Lab when I began working with Dr. Sahagian on this project. Dr. Sahagian had already returned from a visit to Moscow and other areas on the Russian Platform. He was provided with detailed stratigraphic information of each of the sites indicated on figure 1 from published and unpublished reports, and from well descriptions at Centregeologia, Moscow. The data were then organized into tables which are reproduced in appendix I . Information obtained for each site included the following: Province, latitude, longitude, elevation from top, elevation from base, thickness, lithology, environmental deposition, age, and age reliability.

Dr. Sahagian was also able to visit numerous outcrops displaying sediments and rocks from the Oxfordian to the Santonian stage. Detailed descriptions and general geology of the surrounding area was provided by Russian stratigrapher, Alexander Olferiev. A small portion of the samples obtained were sent Martin Farley at the Exxon Production Research Company in Texas for palynologic analysis. Findings are reported in appendix II. The samples were also analyzed in order to provide a complete description of the lithology present for each stage and substage. Descriptions of the lithology are provided in the "stratigraphic analysis" section.

Run Data Through Backstripping Program

A process of imputing the data into the backstripping program can begin once all the required data is obtained. The backstripping equation computes the elevation of sediment above present sea level by: 1) removing one unit at a time, 2) restoring underlying strata to the original thickness prior to compaction, and then 3) isostatic compensates for removal of overburden (Fig 7). Finally, the local water depth is added resulting in the calculated eustatic sea level.

Results: Past Eustatic Sea Level Curve

A computer program (fortran) was developed previously (*Sahagian and Holland*, 1991) to intuitively solve the backstripping equation as successive strata are "removed." The procedure for implementing the program required input of three variables: lithology, water depth, and thickness for each depositional unit. The results can then be plotted for each well on a x-y graph displaying sea level with respect to time (Fig.8). Note that the data is only representative of change in sea level from each interval to the next. This means the y axis is floating. The individual well curves were overlaid and a datum line of current sea level was determined from the present elevation of the strata.

Discussion

Error Analysis

An extensive explanation of various factors introducing possibilities for error in the final eustatic sea level curve has been published by Sahagian and Jones (1993). References to this paper has appeared quite often throughout this report. Therefore, Sahagian and Jones (1993) published work in Geological Society of America Bulletin has been included in appendix 3. This will provide more of a discussion into the interpretations made from the quantified eustatic sea level curve, rather then the methodology into constructing such a curve, as this report has mostly discussed.

Considerations must be made for possibilities of error with any quantitative analysis. In order to make considerations for error, one must be able to identify areas in the methodology which could present some inaccuracies of the end product. The Russian Platform was chosen because it may be the most stable reference frame known, contributing the least amount of error into sea level curve. Biostratigraphy from the Russian Platform is used to determine the age of units and boundaries between units. If these boundaries are not defined at the proper position stratigraphically then the thickness of the unit would be incorrect. However, the quantity of thickness miscalculated for one unit will be added or subtracted in the surrounding units. So over an extensive amount of time miscalculations of unit thickness is not a major factor, and the margin of error is minute (*Sahagian and Jones* ; 1993).

For the backstripping equation, data for lithology, thickness, and water depth had to be imputed. Misinterpretation of any of these introduces error into the eustatic sea level curve. The lithology and thickness are well documented that any misinterpretation would have minimal effects on the curve. Water depth estimates do present a margin of error observable on the sea level curve. These estimates are made easy when analyzing shallow water sediments due to clear facies change and well preserved fossils. A specific water depths has been given for various ocean conditions (Table 1). Water depth for shoreface and lagoonal environments is 2 + 2 m, for transitional environments water depth is 10 ± 5 m, off shore environments are give water depth of 25 ± 10 m (*Sahagian and Jones*, 1993). Error bars for misinterpretation of water depth are included in the graph of the individual wells eustatic sea level curves (Fig. 8). This individual curves do not match with each other exactly, contributing to a banded eustatic sea level curve. This indicates minor amounts of vertical movement did occur during time of deposition, such as variation of compaction.

Applications

A quantified eustatic sea level curve can be very enlightening in itself, but there are some important applications for the curve. For instance, we can apply it to subsiding basins. The eustatic sea level curve is based on a stable reference frame. Thus, if a subsiding basin or a passive margin are forming at the same time, subtracting the eustatic sea level curve from the calculated relative sea level of that area will give the amount of subsidence. Since the age of the strata is known, the range of time can be determined. Once we know the amount of subsidence and the amount of time, the rate of subsidence can then be calculated. The basin subsidence flow chart (Fig. 9) illustrates this procedure. It is important to note, which has been stated continually, using the backstripping method for passive margins, subsiding basins, and other tectonically active regions, results in a relative sea level curve, not a eustatic sea level curve.

An interesting discovery was made when comparing the sea level curve for the Penza region with the sea level curve for the stable Russian Platform. Penza and the Russian Platform "indicate similar sea-level histories from 125 to 65 Ma, but from 135 to 125 Ma, there is an offset of about 25 m. This indicates that either the Penza region subsided during this time interval, or the Moscow region uplifted. We suggest the former on the basis of Penza's proximity to the subsiding Caspian basin. The ability of our analysis to resolve epeirogenic motions of this small magnitude suggests that our quantified eustatic sea level curve can be applied to basin and passive margin stratigraphic data for the purpose of quantifying subsidence history." (*Sahagian and Jones*, 1993)

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TABLE 1. CRITERIA USED IN THIS ANALYSIS FOR ESTIMATING WATER DEPTH AND CHARACTERIZATION OF DEPOSITIONAL ENVIRONMENT

Environment	Criteria	Water depth
Terrestrial	Coals, plants, soils, bauxite, fluvial deposits	-2
Shoreface	Beach, oolites, mudcracks, evaporites, fossils	2
Lagoon	Muds, fossils	2
Reef	Fossils	2
Transition Zone	Storm beds, fossils	10
Offshore	Fossils	25
Deep	Fossils	50

Note: the most reliable environmental data were derived from outcrops, where sedimentary structures and abundant megafossils are available (Sahagian and Holland, 1991). Depositional units are easily correlated in the subsurface short distances to wells and cores between outcrops.

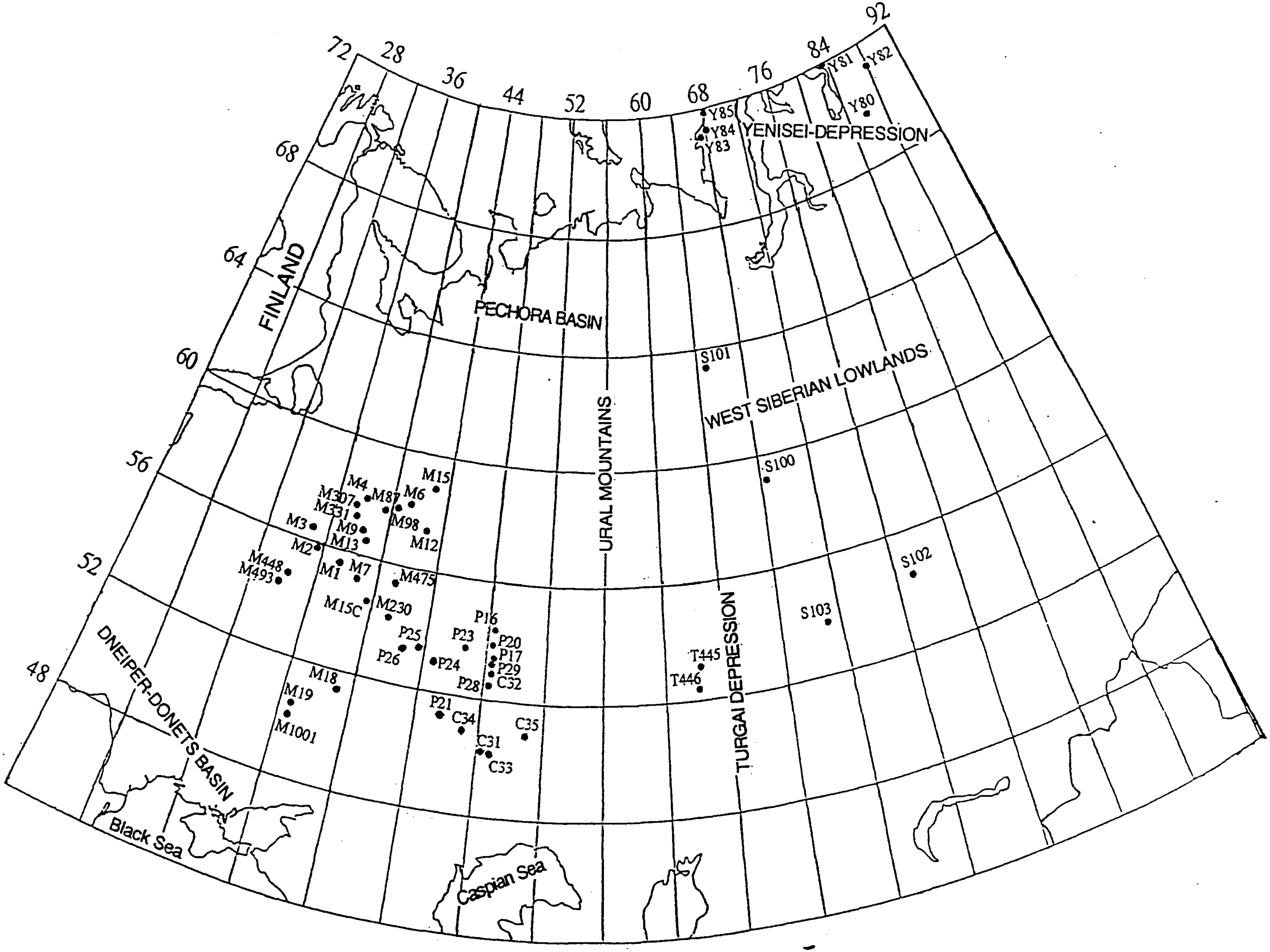


Figure 1: Well location map and surrounding tectonic regions. Wells are first denoted by a letter corresponding to the tectonic region followed by a well number: M = Moscow (much of the Russian Platform), P = Penza, C = Caspian, S = Central West Siberia, Y = Yenisey (northern West Siberia), T = Turgai. Stratigraphic information for each well is given in Appendix I (stratigraphic database) (*Sahagian and Jones*, 1993)

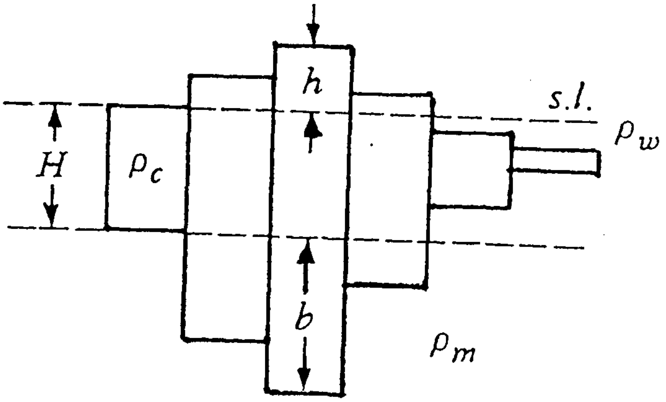
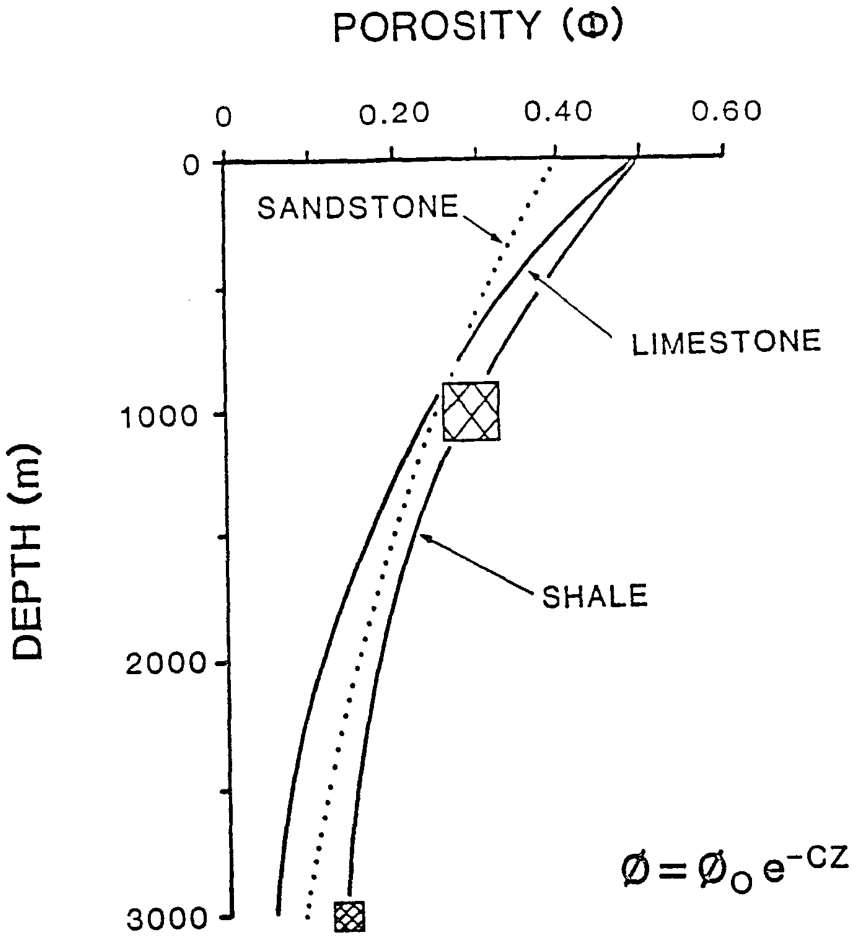


Figure 2: Illustration of Airy model of isostatic compensation (*Turcotte, and Gerald*, 1982, p. 225).



	SHALE	SANDSTONE	LIMESTONE
Φ_0	0.5	0.4	0.5
C m^{-1}	5.0×10^{-4}	3.0×10^{-4}	7.0×10^{-4}
ρ_g	2.72	2.65	2.71

Figure 3: Porosity versus depth curve for shale, sandstone and limestone. Values also given for porosity constants (ϕ_0), decompaction constants (Cm-1), and density constants (ρ_g) (*Angevine, Heller, and Paola*, 1990).

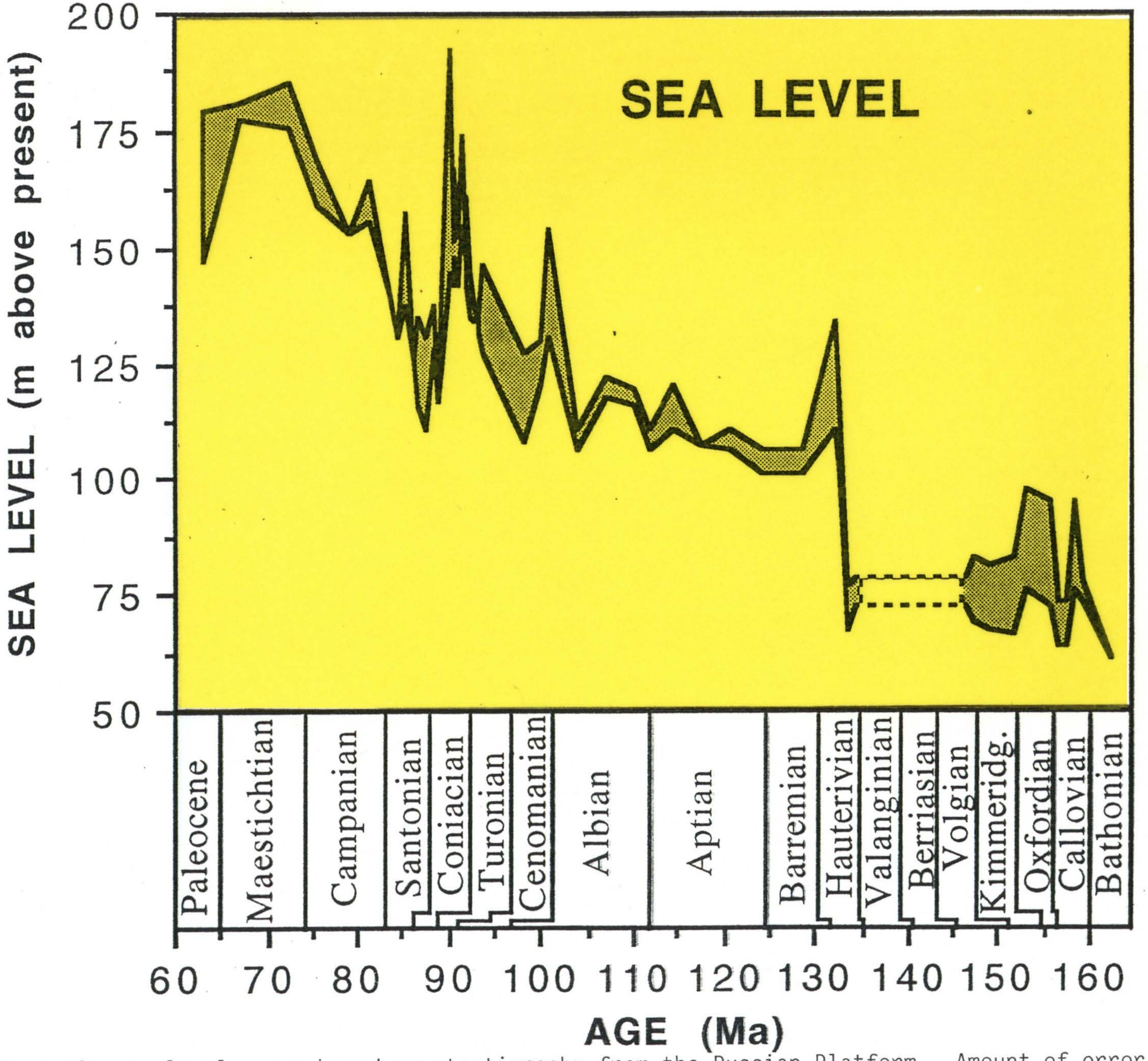


Figure 4: Eustatic sea level curve based on stratigraphy from the Russian Platform. Amount of error is indicative of band width resulting from misinterpretation of water depth and small differences between individual wells.

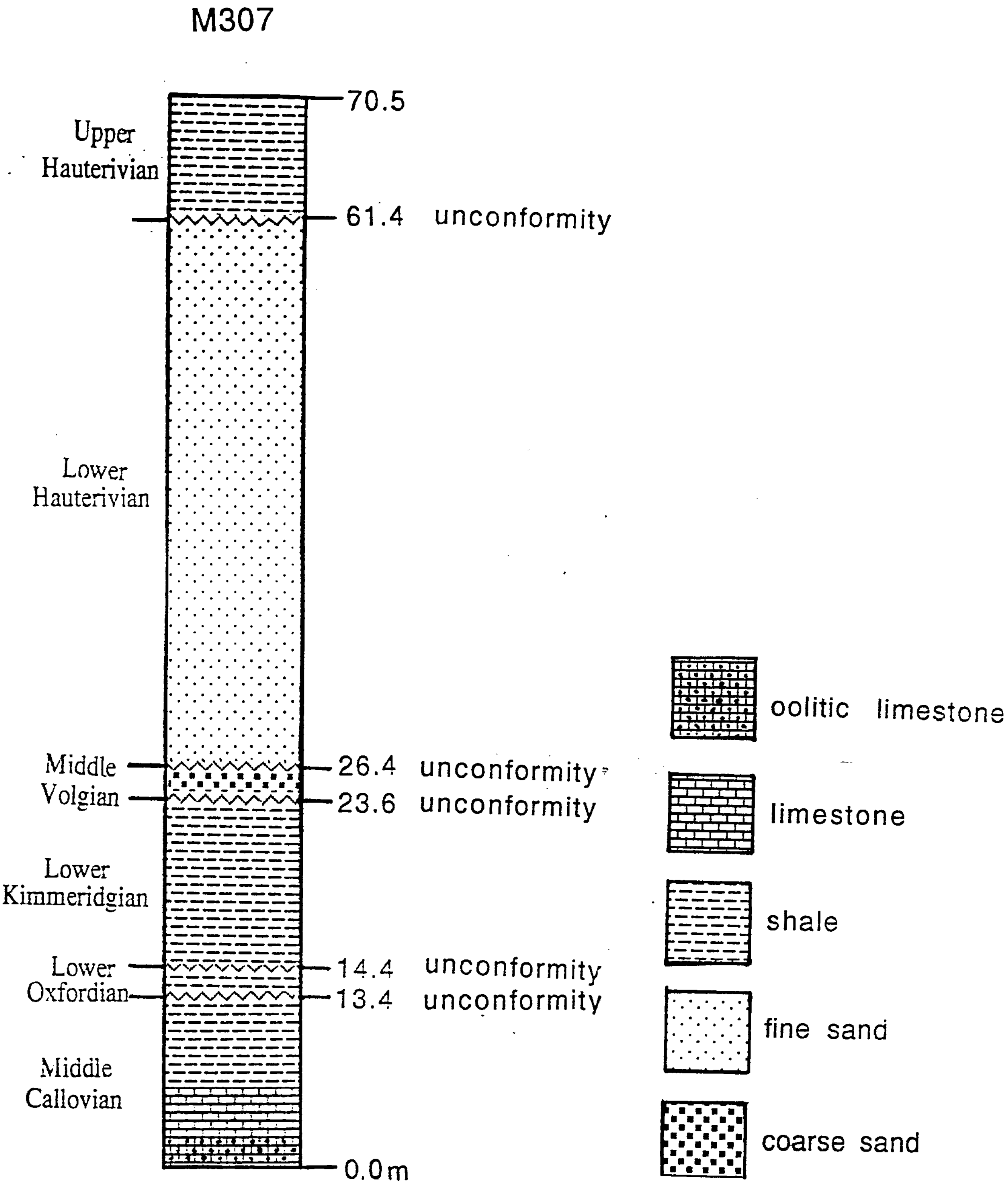


Figure 5: Stratigraphic column for well M307. See figure 1 for geographical location.

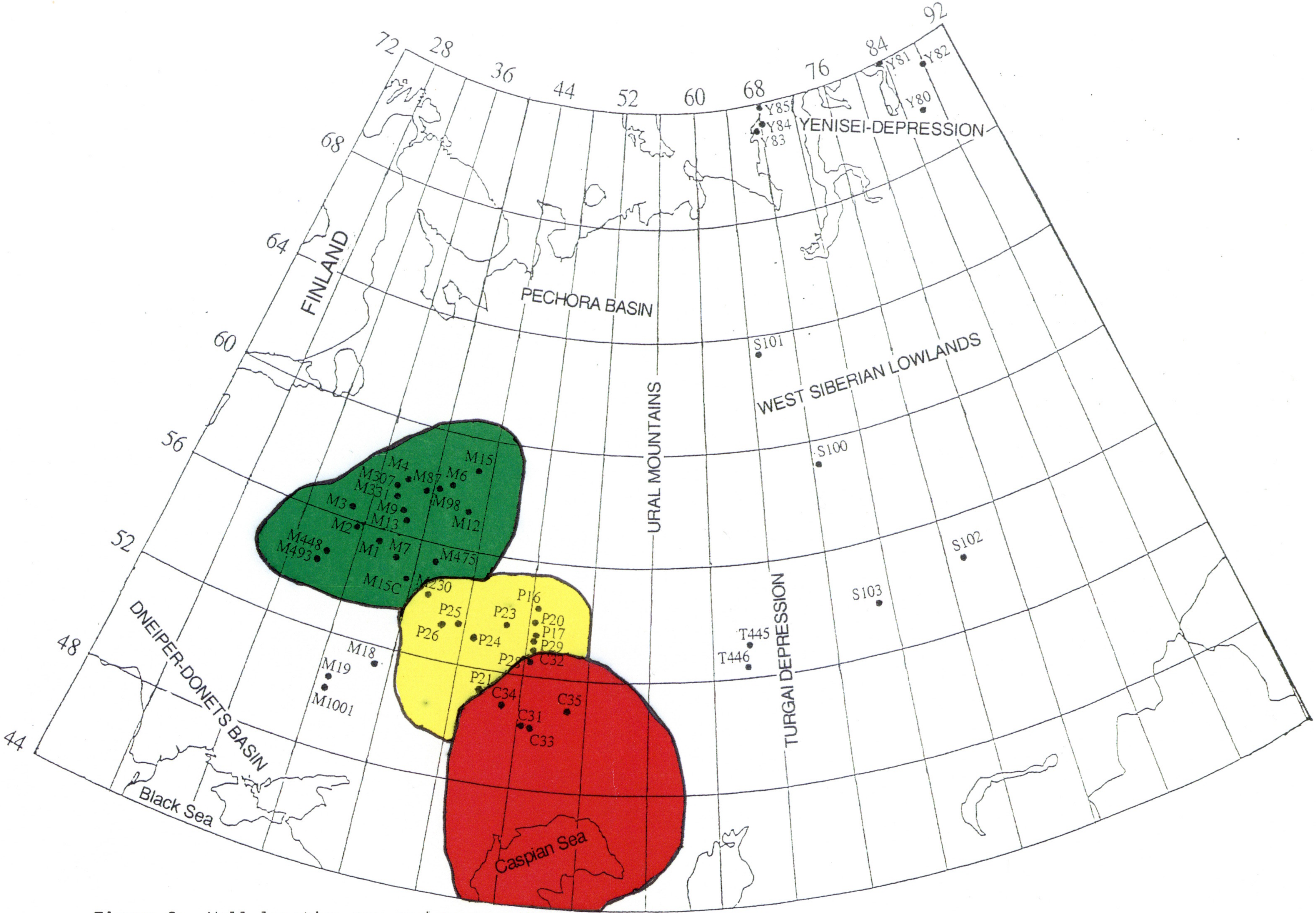


Figure 6: Well location map and surrounding tectonic regions. Green = stable Russian Platform, Yellow = Penza region, Red = Caspian Depression.

Procedural Flow Chart

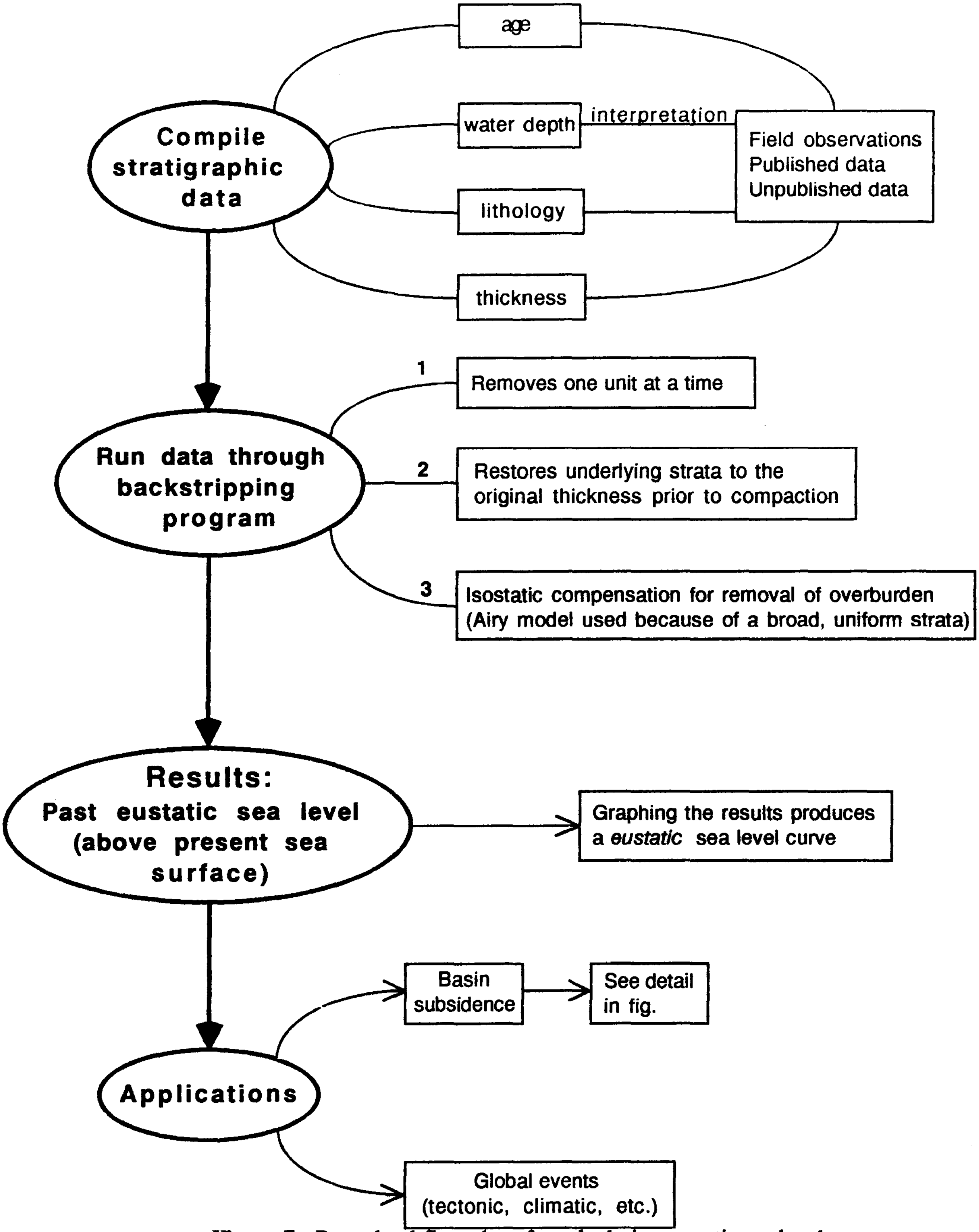


Figure 7: Procedural flow chart for calculating eustatic sea level.

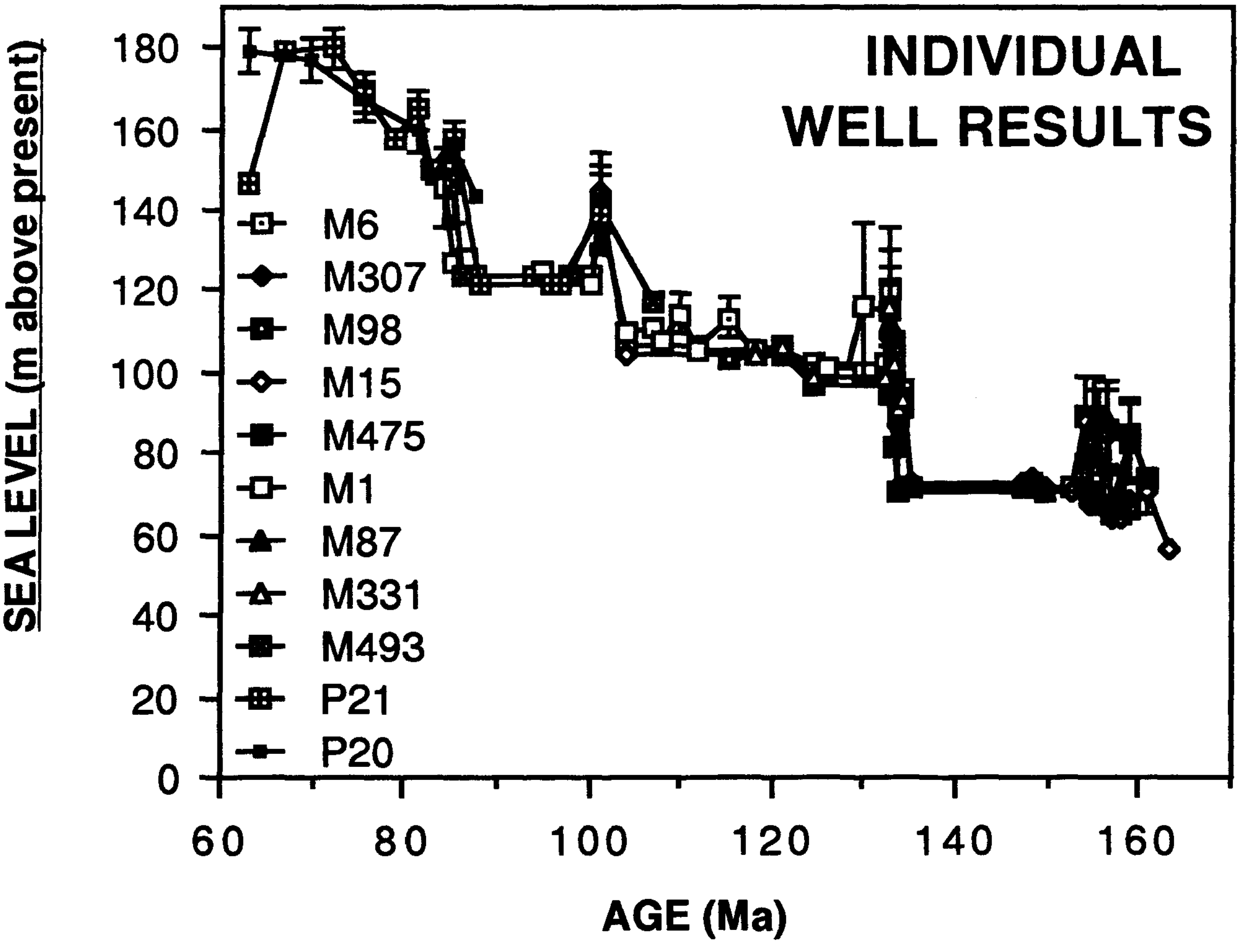


Figure 8: Individual sea level curves from listed wells on the Russian Platform with an addition of 2 wells from Penza. Error bars for improper determination of local water depth are included for each point. Horizontal lines indicate major unconformities in individual sections.

Basin Subsidence Flow Chart

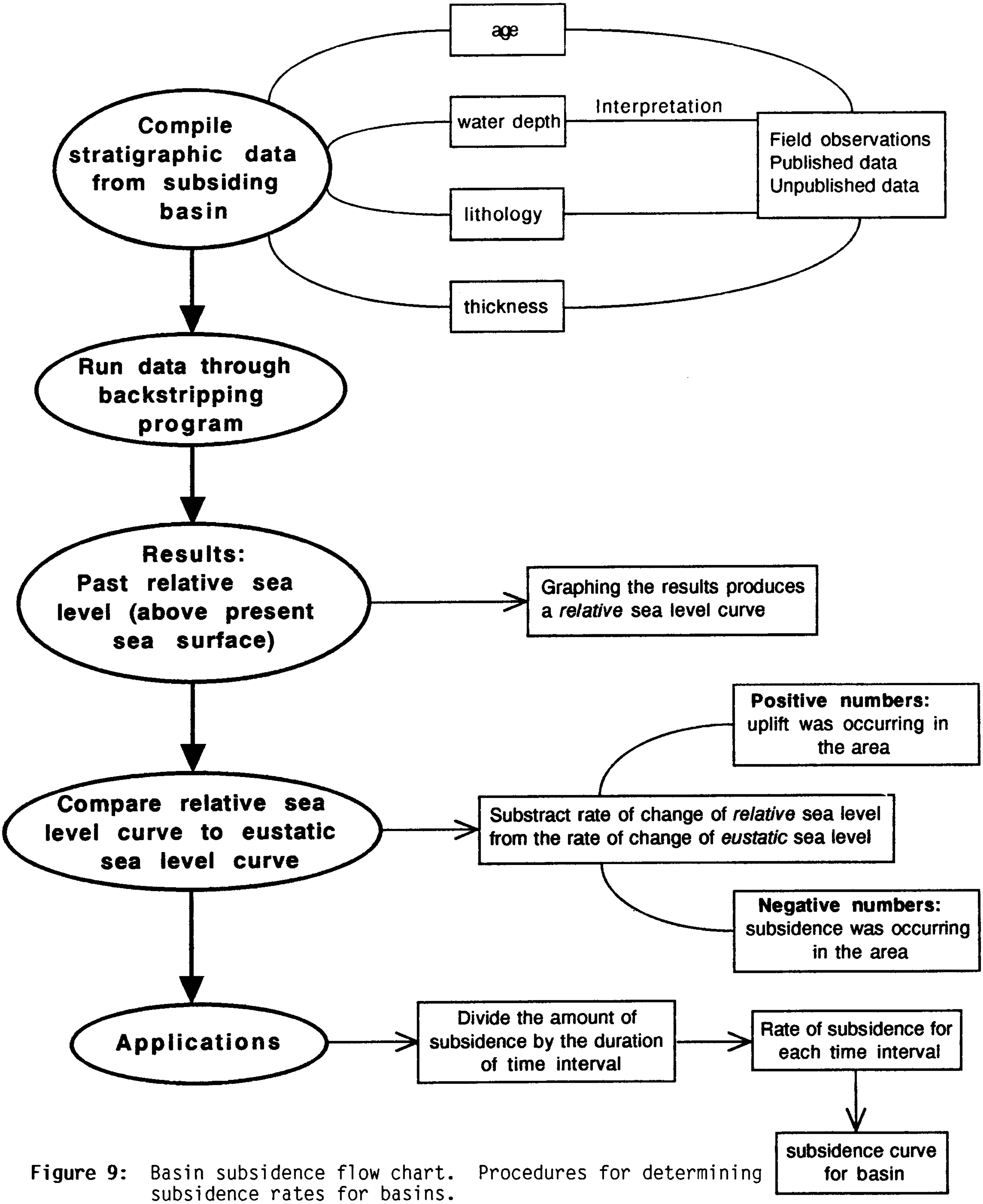


Figure 9: Basin subsidence flow chart. Procedures for determining subsidence rates for basins.

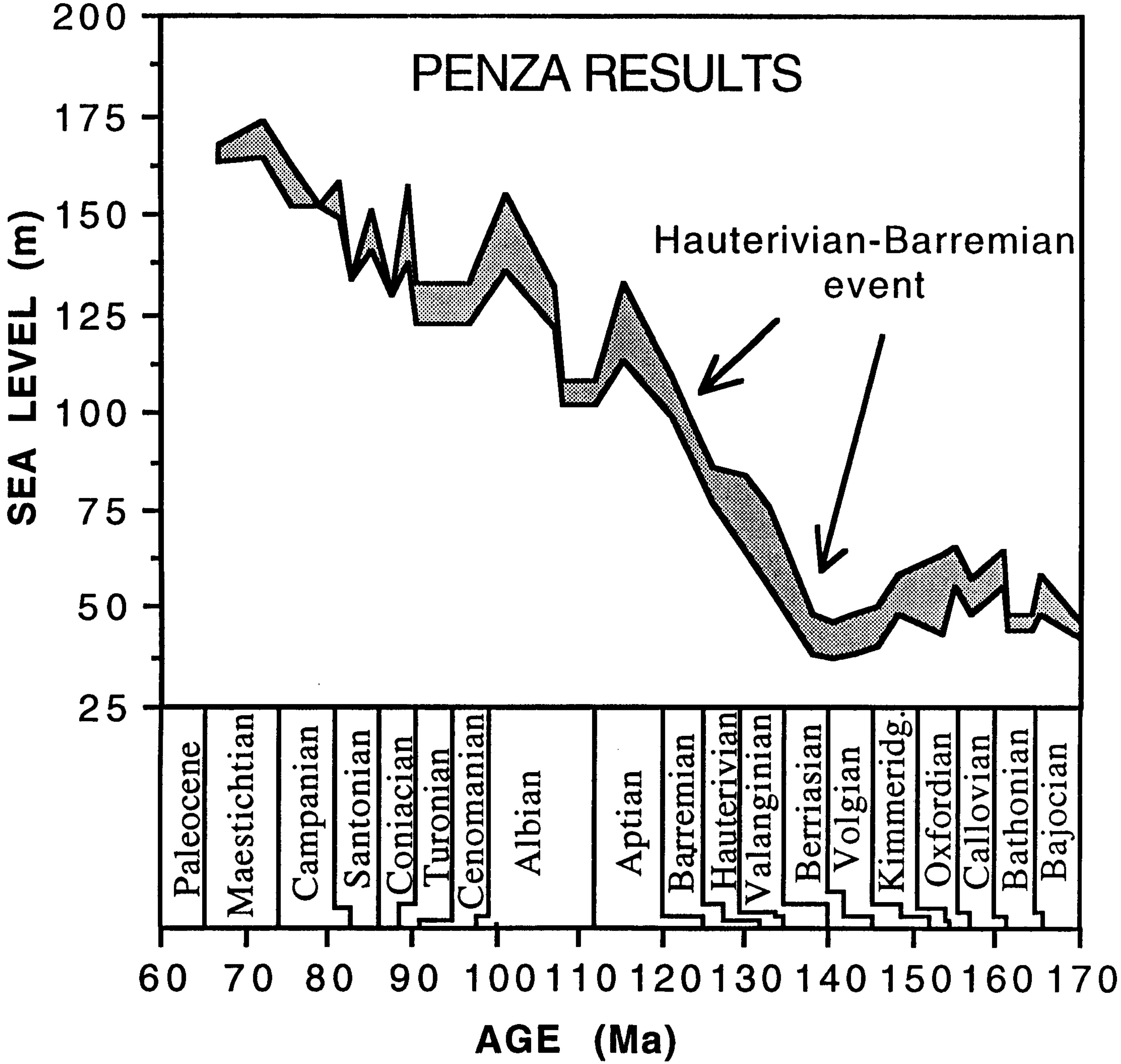


Figure 10: Relative sea level curve for Penza region. Curve is similar to the eustatic sea level curve (125-65 Ma) but then begins to deviate from 160 to 135 Ma. The Penza curve is offset by 25 m.