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**A STUDY OF THE EVOLUTION OF THE  
PROTEROZOIC CUDDAPAH BASIN,  
SOUTH INDIA**

by

**STANLEY SCHLEIFER**

**A dissertation submitted to the Graduate Faculty in  
Earth and Environmental Sciences  
in partial fulfillment of the requirements for the degree of  
Doctor of Philosophy,  
The City University of New York**

**1996**

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**This manuscript has been read and accepted by the Graduate Faculty in Earth and Environmental Sciences in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.**

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## **Abstract**

### **A STUDY OF THE EVOLUTION OF THE PROTEROZOIC CUDDAPAH BASIN, SOUTH INDIA**

by

**Stanley Schleifer**

**Advisor: Professor Somdev Bhattacharji**

**The Cuddapah Basin of the peninsular Indian shield, is a Proterozoic, intracratonic, sedimentary basin. Questions have been raised concerning the mechanisms for the origin and evolution of this basin, and other Proterozoic basins on the Indian shield and about the relative vertical movements of sub-basins which have been identified within the Cuddapah Basin. Computer simulations of thermally induced basin development and evolution are used to address these questions. The simulations indicate that thermal driving forces can account for the development and evolution of the Cuddapah Basin and similar Proterozoic intracontinental basins. Model simulations of heat redistribution with time in crystalline rocks, indicate that a single magmatic event could not account for the 600 million to 1 billion year history of tectonic evolution of the Cuddapah Basin. Evidence derived from**

**radioisotope dating of igneous rocks within, or near the basin, suggests that at least three distinct periods of magmatic activity, separated in time by over three hundred million years, were involved in the evolution of the Basin. Computer enhanced Landsat images of the Cuddapah Basin area have been enhanced, analyzed, and compared with deep seismic sounding (DSS) profiles across the basin to locate deep lithospheric fractures and/or faults which define boundaries of the basin and of sub-basin areas within the basin. The study suggests that the Cuddapah sub-basins were stress-decoupled from one another during their evolution and significant stresses due to vertical movements, were not transmitted across the pre-existing zones of weakness in the Archean lithosphere. This has enabled the sub-basins to exhibit independent vertical motion and to behave as yoked basins. Because of the significant differences in the geothermal and chemical environment of the crust and upper mantle during Proterozoic time as compared to Phanerozoic time, it is considered unlikely that Proterozoic intracratonic basins such as the Cuddapah Basin have Phanerozoic analogues.**

## **Acknowledgements**

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**The author thanks the members of his Committee for their help and patience as well. The author would like to thank Professor Alan Ludman in particular for going "above and beyond the call of duty" to help improve this thesis.**

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**The author would also like to acknowledge his mother, who has helped and encouraged him all of his life and to honor her memory, for she unfortunately did not live to see him complete this work.**

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## **I n t r o d u c t i o n**

**The Proterozoic Era was a critical time of transition in the evolution of the earth and its life forms. It was a time of important chemical changes in the surface environment of the earth. It was during this time, that the partial pressure of oxygen in the earth's atmosphere is believed to have exceeded the critical "Pasteur Level", (about 1% of the present atmospheric level; Windley, 1977). This made possible the development of eukaryotic life forms (Schildowski, 1971, 1976). During this time, the banded iron formations of the Archean were being replaced by the continental red beds typical of Proterozoic and later deposits.**

**The pH of the earth's ocean waters increased from Archean to Proterozoic time, changing the chemical environment of the seas from acid to slightly alkaline in nature. Among other things, this facilitated the precipitation and deposition of carbonate sediments during Proterozoic and later times. During the Proterozoic, the nature of carbonate sedimentation was changing from predominantly primary dolomitic carbonates to limestone (Windley, 1977).**

**Evidence of changes such as those described above is preserved in the lithology and chemical characteristics of sedimentary rocks of Proterozoic age. The Proterozoic intracratonic basins containing such rocks give us information about the biota and about the chemistry of the atmosphere and surface waters during**

**Proterozoic time, and also about the location and lithology of the source rocks of the basin sediments.**

**Changes in the rate of radiogenic heating of the rocks of the crust and mantle were reflected in changes in tectonic style from the Archean to the Proterozoic (Strong and Stevens, 1974; Salop and Scheinmann, 1969). The Archean was characterized by the rapid differentiation and accumulation of continental material due to extensive upper mantle melting and the resulting magmatism forming many relatively small proto-continental masses at the surface of the earth (Windley, 1977). By the close of the Archean Era, radiogenic heating by the decay of elements such as uranium 235 and potassium 40 had decreased significantly, and outgassing had moved the mantle peridotite solidus upward. Thus, most of the presently observed volume of continental crust had already fractionated from the mantle by this time (Strong and Stevens, 1974; Armstrong and Hein, 1973).**

**As a result, the Proterozoic was a time of changing tectonic style, from microplate tectonics to macroplate, (or modern), tectonics. The microplate stage is believed to have culminated in a worldwide cratonization event, (circa 2.5 Ga), which is generally accepted as the Archean - Proterozoic boundary. Cratonization did not stop entirely at the Archean-Proterozoic boundary, but recurred locally well into the Proterozoic (Miall, 1990; Rogers et al, 1984).**

**By Proterozoic time, most of the small Archean protocontinental masses had**

coalesced to form larger continental masses, perhaps, as many workers in the field believe, a Proterozoic supercontinent (Piper, 1976). As the rigidity of the continental lithosphere approached present values during the Proterozoic, modern, (i. e. Phanerozoic) style continental margin type plate tectonics could begin (Windley, 1977).

Many aspects of Proterozoic tectonics are poorly understood or are controversial in the scientific community. One such area concerns the intracratonic basins that appeared, apparently in large numbers all over the earth during the Proterozoic Era, particularly on the peninsular Indian crust (Bhattacharji, 1987; see Figure 1). These Proterozoic basins have been described by some workers as aulacogens (Salop, 1983), by others as forearc type basins (Prasad et al, 1987), and by others as Proterozoic analogues of Phanerozoic basins such as the Michigan or Williston basins. There are problems with each of these interpretations, and further study is needed to gain a better understanding of the evolution of Proterozoic intracratonic basins.

Proterozoic intracratonic basins such as the Cuddapah Basin of southern India, contain important information, not only concerning the surface environment but also about the tectonic evolution of the earth during this critical time. Igneous rocks in, around, or associated with these Proterozoic basins provide evidence of mantle related magmatic activity that might have been related to the tectonic

**processes involved in the formation and evolution of the basins. (Nagaraja Rao et al, 1987). The Indian Proterozoic intracratonic basins are the site of important concentrations of mineral resources. These include; diamonds, asbestos, barite and phosphorite (op. cit., 1987).**

## **Geologic Setting**

**The Cuddapah Basin, the largest of the Proterozoic basins on the Archean shield of Southern India (see Figure 1) is considered by many geoscientists to be also the best exposed and best preserved, in terms of observable sedimentary sequences and structural relationships. Because of this, the Cuddapah Basin deposits have become recognized as a strato-type for Indian Proterozoic basins (Bhattacharji, 1987). Therefore, by studying the Cuddapah Basin, we can gain critical insight into Proterozoic environments and tectonic processes.**

**The Peninsular Indian subcontinental lithosphere, on which the Cuddapah Basin was superposed, is a mosaic of several different crustal blocks which were joined or sutured together to form a continental mass by mid-Proterozoic time. This continental mass is believed to have been part of a mid-Proterozoic Supercontinent (Piper, 1976; see Figure 2).**

**The Cuddapah Basin is a crescent shaped, intra-cratonic basin containing rocks of middle to upper-Proterozoic age, which lie unconformably over Archean gneisses of the Dharwar Supergroup (King, 1872; see Figure 1). The rocks of the Dharwar Supergroup are believed to be about 2500 to 3000 my. old, (Naqvi, 1976; Salop, 1983), and probably correspond to Greenstone Belt sequences in other locations (Nagaraja Rao et al, 1987). The rocks of the Cuddapah Basin are**

presently exposed over an area of 44,500 km<sup>2</sup> (Rao et al, 1987; King, 1872). The basin is approximately 440 km long with a concave eastern margin, and is about 145 km across at its maximum width. The basin contains sedimentary, meta-sedimentary and igneous rocks to a maximum thickness of about 12 km (op. cit.).

There are extensive, well exposed Archean basement rocks surrounding the Cuddapah Basin. These were the basement on which the basin sediments were deposited, and into and/or through which the magmas associated with basin evolution were intruded. This permits the observation of the lineaments in this Archean basement, possibly representing faults and/or fractures, which might have been a major factor in the location of the Proterozoic basins forming on the Archean crust (Bhattacharji, 1987; see Figure 5).

The Cuddapah Basin has been the focus of commercial as well as scientific interest and investigation ever since the early diamond workings, mainly from alluvial deposits in and around the Krishna valley, were described by the famous French explorer Tavernier, as reported by Ball (1925). Diamonds have also been discovered from kimberlite diatremes in the Archean basement rocks around the Cuddapah Basin (Radhakrishna, 1987).

In recent years, the economic value of the rock and mineral resources of the Cuddapah Basin has stimulated exploration and increased scientific interest.

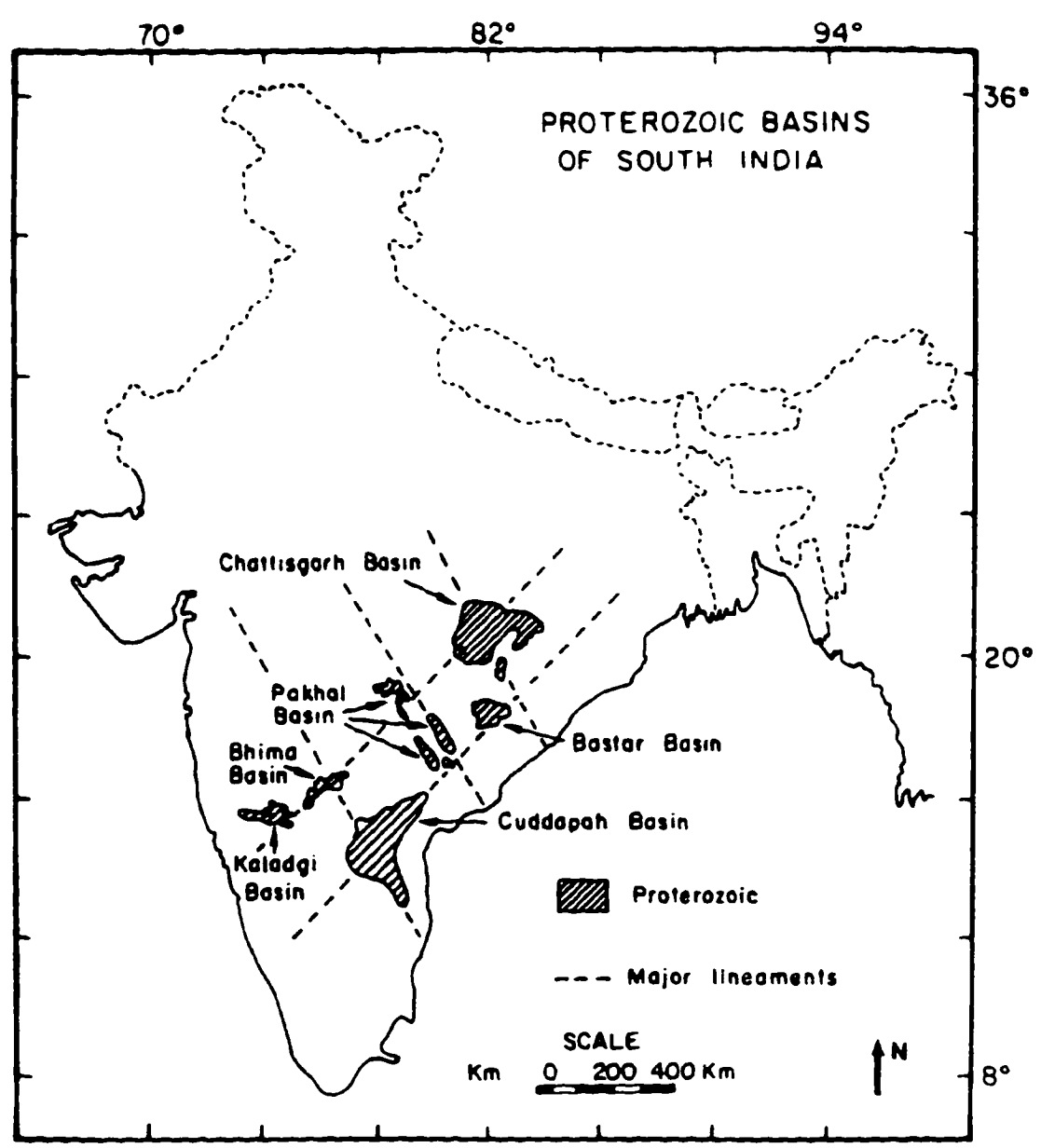


Figure 1. Proterozoic Basins of Southern India (From Bhattacharji, 1987)

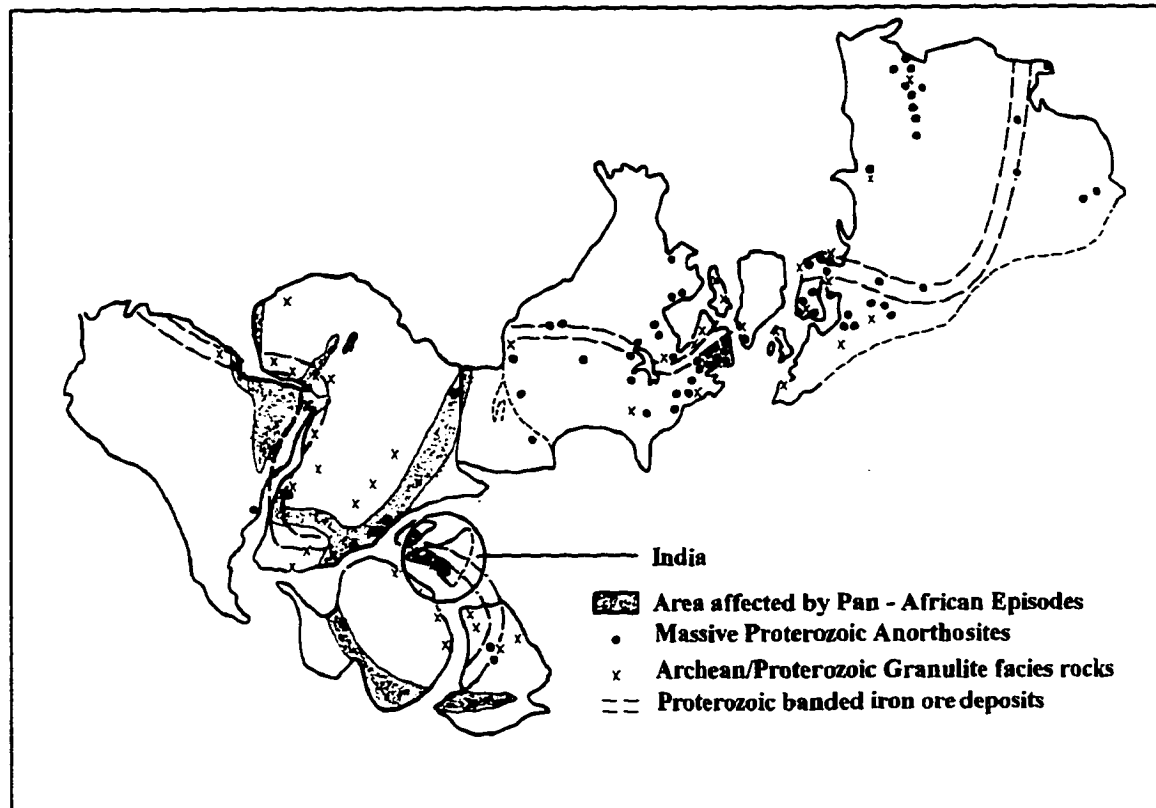


Figure 2. Proterozoic Supercontinent (after Piper, 1976) modified from Windley, 1977)

In addition to the diamonds mentioned above, these include; asbestos, barite (over 25% of the world's known reserves), base metals (lead, copper and zinc ores), cement grade carbonate deposits, building stones (serpentinized dolostones which are particularly prized for their color and shading), chemical grade limestones,

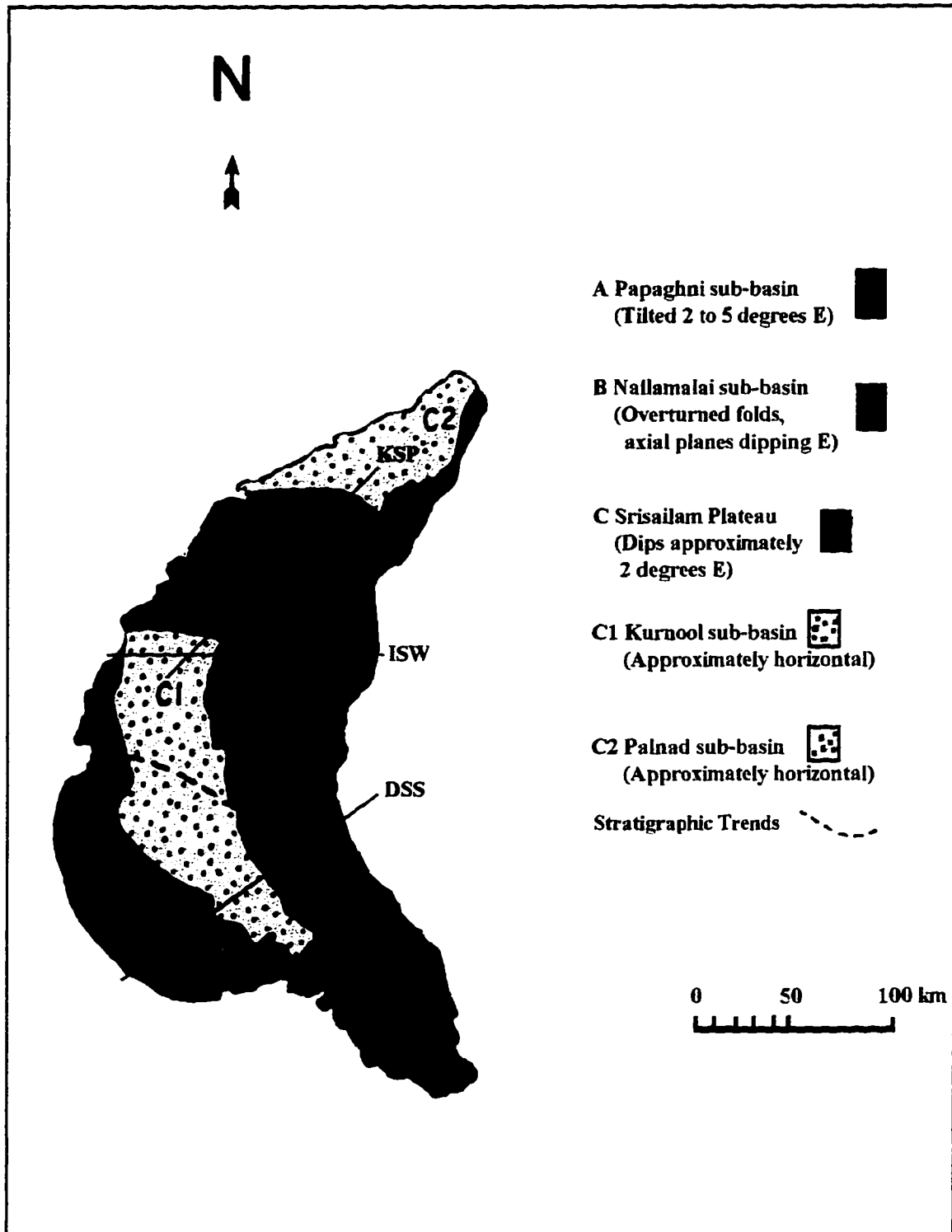
**flaggy bedded sandstones, used for building, which are known in India as "Cuddapah slabs", phosphorite deposits, and good quality slates (Nagaraja Rao et al, 1987). The economic and strategic value of the resources associated with the Cuddapah Basin is yet another incentive for modern geoscientists to better understand it, and the processes by which it has evolved.**

## **Previous Work**

**The earliest systematic geologic field mapping of the Cuddapah Basin, (known to the author), was done by Oldham, King and Foote as synthesized and reported by King in his memoir of 1872 (King, 1872). The next significant revision of geological mapping relating to the Cuddapah Basin was by Coulson, (1934). Coulson did detailed geological mapping of parts of the Vempalle formation in the western side of the basin, as part of an exploration of the occurrence of asbestos in this area. (This is a high quality, serpentine asbestos, found along the upper and lower contacts of mafic sills with the dolomitic rocks of the Vempalle formation.)**

**Sen and Narasima Rao (1967) were the first known to consider the relationship of episodes of magmatic activity associated with the Cuddapah Basin, as evidenced by bodies of igneous rock, in and around the basin, with the evolution of the basin itself. This concept has formed the basis for much of the subsequent work done in modeling the processes forming the Cuddapah Basin as well as other, similar basins (Nagaraja Rao et al, 1987).**

**The Cuddapah Basin has been divided by many workers (eg. Murthy and Reddy, 1984) into five sub-basins (see Figure 3). These include; the Papaghni, Nallamalai, Srisailam, Kurnool and Palnad sub-basins. These divisions are based on the structural and stratigraphic relationships of the sedimentary formations within the basin (see Figures 4, 5, and 7).**



**Figure 3.** Sub-basins of the Cuddapah Basin (Modified from Murthy and Reddy, 1984) (ISW, DSS and KSP locate cross sections through the Iswarakuppam Dome, DSS profile, and Srisaillam Sub-basin, respectively.)

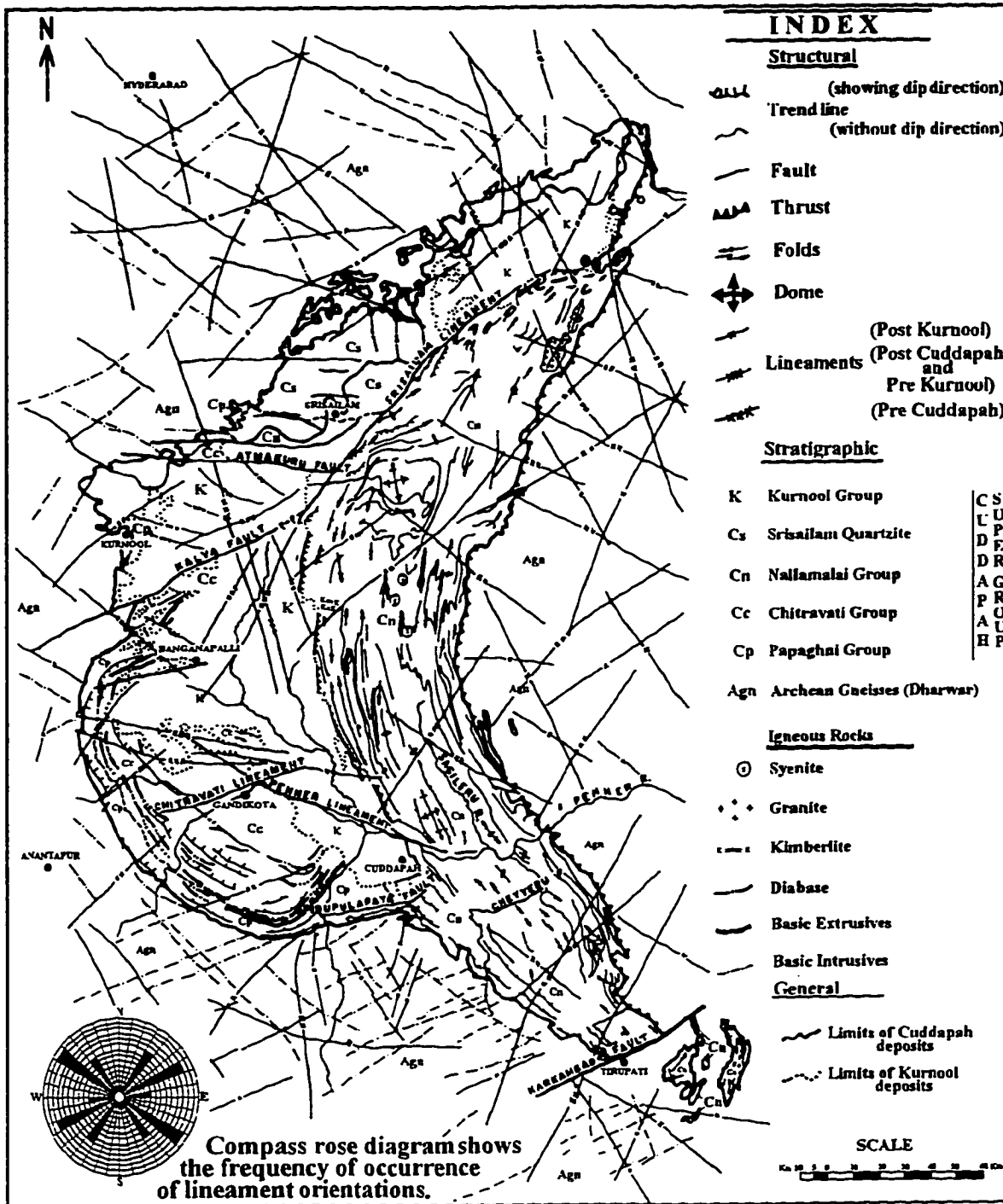


Figure 4. Geological Map of the Cuddapah Basin (Modified from Rao et al, 1987)

**The stratigraphy of the sub-basins of the Cuddapah Basin, as well as the relationship of these depositional sequences to one another, has been refined by more recent work. Dutt (1975) identified the contact between the Panem Quartzite and the Auk Shale as a disconformity and therefore, showed that the Kurnool/Palnad sediments should be considered as a supergroup. Narayanswami (1976) presented a revision of King's (1872) stratigraphy of the Cuddapah Basin, separating the Chitravati as a separate depositional group from the Cheyair Group (see Table 1 and Figure 5 in the stratigraphy section, for a summary of Cuddapah Basin stratigraphy).**

## **Purpose of Study**

**Although the Cuddapah Basin has been the subject of many scientific investigations, numerous questions concerning the mechanism and timing of its origin, and the evolution and activity of the basin over a period of time estimated to be on from 700 million to a billion years (Bhattacharji, 1987; Rao et al, 1987)7 remain unresolved. These include the following:**

- (i) Was the deposition of the basal sediments in the Cuddapah Basin synchronous with that of the other Proterozoic basins on the Indian Archean shield? If so, were all of these basins formed as part of the same depositional event?**
- (ii) Is the initiation, and development of these basins related to a widespread magmatic event, or events, originating in the mantle, and occurring during, and/or prior to, their evolution?**
- (iii) What were the mechanisms involved? Can the thermal effects, due to the emplacement of a mantle plume into the crust account for the observed thickness of sedimentary rock in the Cuddapah Basin and other similar Proterozoic intracratonic basins ?**

- (iv) **Do these Proterozoic intracontinental basins have younger intracontinental analogues, such as the Michigan and Illinois Basins, or were the particular conditions necessary for the formation of the Proterozoic basins, such as those on the Indian Shield, including the Cuddapah Basin, unique to the Proterozoic Era?**
- (v) **Could an intracratonic basin such as the Cuddapah Basin have been formed as a result of a single thermal event or are episodes of thermal reactivation necessary to explain the long history of activity evident in the basin?**
- (vi) **Have the sub-basins within the Cuddapah Basin moved vertically with respect to one another? If so, what was the mechanism involved?**
- (vii) **Why are formations in the eastern part of the Cuddapah Basin intensely folded and faulted while older formations in the western part of the basin remain relatively undeformed?**

**In this study, the author attempts to gain some insight into the answers to these questions by means of computer simulations of thermally driven, vertical basin**

**movements, and by the identification of large scale lineaments as revealed by computer enhanced, Landsat derived imagery of Southern India in order to delineate "lithospheric blocks", bounded by these lineaments. These "lithospheric blocks" apparently underlie the sub-basin areas within the Cuddapah Basin (see Figure 4, Figure 6, and Plate 1).**

## **Stratigraphy**

**Cuddapah Basin sedimentation occurred in four distinct phases that affected different sub-basin areas at different times. These deposits are assigned to two major stratigraphic units; the Cuddapah and Kurnool Supergroups (Table 1 and Figure 5). The Cuddapah Supergroup consists of strata deposited in the Papaghni, the Nallamalai and Srisailam sub-basins. Kurnool Supergroup deposits are found in the Kurnool and Palnad sub-basins (Figure 3).**

### **Papaghni sub-basin:**

**The Papaghni sub-basin at the western margin of the basin records the earliest Proterozoic sedimentation in the area (Figures 3 and 4). These deposits are assigned to the Papaghni Group and the Chitravati Group. The Papaghni sediments are divided into the Gulcheru and Vempalle formations (see Figure 5a).**

**The Gulcheru Formation is the oldest formation in the Cuddapah Supergroup. It unconformably overlies the Archean rocks of the Dharwar Supergroup and passes upward into the Vempalle Formation. The Gulcheru is a thin clastic unit consisting of a basal conglomerate, overlain successively by arkose, quartzite and shale. The basal conglomerate contains pebbles and cobbles of quartz and jasper rather than fragments of unweathered granitic basement. This would be consistent with an origin as lag deposits on the eroded basement as suggested by Bhattacharji (1987). The thickness of the Gulcheru formation is greatest in the**

southern part of the sub-basin (Jahnwar et al, 1964).

The upper Gulcheru contains coarse grained fluvial sandstones, with well developed cross-bedding and (in many areas) significant amounts of olivine, pyroxene and epidote. This would indicate mafic and ultramafic rocks in the source area. (Dasgupta, 1985 personal communication to S. Bhattacharji, as reported by S. Bhattacharji, 1987) The fact that the olivine, pyroxene and epidote were not removed by chemical weathering, suggests that the source rocks were relatively close to the site of deposition in the sub-basin. (The surrounding Archean basement contains extensive mafic intrusives; Nagaraja Rao et al, (1987)).

The Gulcheru is conformably overlain by the much thicker Vempalle Formation. The Vempalle contains stromatolitic dolostone, calcareous shale, chert and chert breccia, sandstone and quartzite. These are overlain by basaltic lava flows representing at least two episodes of volcanic activity (Bhattacharji, 1987; see Figure 5a).

The Vempalle shows a progressive deepening of the basin as indicated by sediments deposited in a lower energy environment than those of the Gulcheru. (This would indicate that during this time, the rate of subsidence exceeded the rate of sedimentation). The argillaceous sediments show glide structures dipping to the east and also show an occasional return to shallower water and somewhat higher energy conditions of deposition.

**The Vempalle Formation is unconformably overlain by the deposits of the Chitravati Group, also within the Papaghni sub-basin but centered further to the east than the Papaghni Group. They consist of the Pulivendla, the Tadpatri, and the Gandikota formations (Figure 5b).**

**The Pulivendla Quartzite overlies an erosional surface on the Vempalle Formation. It is an orthoquartzite with a conglomeritic base (Rao et al, 1976). Like the Gulcheru, the Pulivendla may be considered as having a basal conglomerate. However, the Pulivendla is much thinner than the Gulcheru and it is not arkosic.**

**The Tadpatri Formation conformably overlies the Pulivendla Quartzite. It is a primarily argillaceous unit with minor calcareous to dolomitic intercalations indicating an alternate deepening and shallowing of the basin sea (Rao et al, 1987). Tadpatri shales include some volcanic ash falls and tuffs which tend to be felsic in composition, as well as mafic intrusives (sills), and extrusives (flows). Some of the dolomitic layers of the Tadpatri Formation contain stromatolite fossils (Rao et al, 1976).**

**The Gandikota Formation lies conformably over the Tadpatri Formation with a gradational contact. It is an essentially clastic unit, consisting of quartzite and shale (Rao et al, 1987).**

**Nallamalai sub-basin:**

**The Nagari, Bairenkonda, Pullampet and Cumbum formations comprise the Nallamalai Group and lie within the Nallamalai sub-basin (Table 1, Figures 3, 5c and 5d). The Northern Nallamalai deposits consist of the Bairenkonda and Cumbum formations (Figure 5c). The Southern Nallamalai deposits consist of the Nagari and the Pullampet formations (Figure 5d).**

**The Nagari Quartzite is exposed primarily in the southern part of the Cuddapah Basin. There it overlies, with angular unconformity, the Gulcheru and Vempalle Formations of the Papaghni Group. Further south, it unconformably overlies Archean basement rocks of the Dharwar Supergroup. The Nagari Formation is a clastic unit, consisting of a basal conglomerate with an overlying quartzite and minor shales. Glauconitic horizons with ripple marks and cross-bedding indicate a shallow marine to littoral environment of deposition (Nagaraja Rao et al, 1987). Sills of olivine diabase are also reported within the Nagari Formation (Dutt, 1975). The basal conglomerate is oligomicritic, consisting mainly of quartzite pebbles. Constituents of the basal material in the Nallamalai are reportedly derived from the rocks of the Papaghni and Chitravati Groups (Nagaraja Rao et al, 1987).**

**The Bairenkonda Quartzite, exposed in the northern part of the Cuddapah Basin, correlates with the Nagari Quartzite to the south (Rao et al, 1987). This**

unit is for the most part a quartz arenite, with some slate/shale seen in the area of the Iswarakuppam Dome (Figure 4, Geologic Map of the Cuddapah Basin).

The Cumbum and Pullampet Formations lie conformably over the Bairenkonda and Nagari formations, respectively. They are argillaceous units with minor calcareous intercalations. The Cumbum Formation contains some bedded chert. Some of the argillaceous rocks of the Cumbum are metamorphosed to slate and phyllite, others remain essentially shale (Nagaraja Rao et al, 1987).

According to Rao et al (1987), the rocks of the Cumbum and Pullampet Formations are correlative, and are observed to grade into one another in the vicinity of the Iswarakuppam Dome.

#### **The Srisailam Plateau:**

The Srisailam Formation is a glauconitic, ferruginous quartzite. There are minor shaley intercalations (Rao et al, 1987). This is indicative of a high energy, near shore, shallow water environment of deposition.

Meijernik et al (1983) place the Srisailam Quartzite below the Pullampet Formation in the Nallamalai Group. However, Rajuarkar and Ramalingaswami (1970), observed the Srisailam Quartzite lying unconformably over folded members of the Nallamalai Group. This establishes the Srisailam Quartzite as separate from, and younger than, the Nallamalai Group. This angular unconformity, with the Srisailam overlying members of the Nallamalai Group, has been identified in other

locations by Satapathy (1979) and by Ramalingaswami (1976).

**The Kurnool and Palnad sub-basins:**

The formations of the Kurnool Group are found in the Kurnool and the Palnad sub-basins (Figures 4 and 7a). These units lie unconformably over rocks of the Papaghni, the Nallamalai, and the Srisailam Groups (Figures 4 and 5e).

The Banganapalle Formation appears to contain a basal conglomerate. It is glauconitic, exhibiting cross-bedding, ripple marks and mud cracks. This indicates a shallow marine to supratidal environment of deposition (Clifton, 1973).

The Narji Formation is for the most part, a dark grey micritic limestone. It is pyrite bearing indicating a reducing environment of deposition. However there are intraformational conglomerates and glauconite bearing quartzites indicating occasional sub-aerial conditions as well (Nagaraja Rao et al, 1987).

The Auk Shale is siliceous and ferruginous, indicative of a near shore environment of deposition.

The Paniam Quartzite contains very mature sediments and shows cross-bedding also indicative of a near shore environment (Nagaraja Rao et al, 1987).

The Koilkuntla Limestone is similar to the Narji and also reflects a shallow marine reducing environment (Nagaraja Rao et al, 1987).

The Nandyal Shale is the youngest unit present within the Cuddapah Basin. It is calcareous and purple in color which reflects a shallow marine, oxidizing

environment. It also exhibits mudcracks in some horizons, indicating occasional sub-aerial exposure.

The lithostratigraphy of the Cuddapah Supergroup and the Kurnool Group is summarized below:

**Table 1**  
**Lithostratigraphy of Cuddapah Basin Sediments**  
(Modified from Rao and Ramlingaswamy, 1976)

|  | <u>Group</u>               | <u>Formation</u>         | <u>Thickness (meters)</u>        | <u>Lithology</u>                                     |  |
|--|----------------------------|--------------------------|----------------------------------|--|--|
| K<br>S<br>G*                                   | *Kurnool<br>Super<br>Group | Nandyal Shale            | 50 - 100                         | Shale  |  |
|  |                            | Koilkuntla ls.           | 15 - 50                          | Limestone  |  |
|  |                            | Paniam Quartzite         | 1- 35                            | Quartzite  |  |
|  |                            | Owk Shale                | 10 - 15                          | Red Shale  |  |
|  |                            | Narji ls.                | 100 - 200                        | Limestone  |  |
|  |                            | Banganapalli Fm.         | 10 - 50                          | Conglomerate   |  |
|  |                            | ----- Unconformity ----- |                                  |  |  |
| C<br>u<br>d<br>d<br>a<br>p<br>a<br>h           | Srisailem<br>Group         | Srisailem Quartzite      | 300                              | Quartzite + Shale                                    |  |
|  |                            |                          |                                  | ----- Unconformity -----                             |  |
|  |                            |                          | Cumbum Fm.                       | 2000   | Phyllite, Slate, Quartzite, Dolomite                                 |
|  |                            |                          | Pullampet Fm.                    | (Included with Cumbum)                               | Shale, Dolomite, Quartzite   |
| S<br>u<br>p<br>e<br>r<br>g<br>r<br>o<br>u<br>p | Nallamalai<br>Group        | Bairenkonda Fm.          | 1500                             | Quartzite, shale                                     |  |
|  |                            | Nagari Fm.               | 4000                             | Conglomerate, Quartzite, Shale, Intrusives)          |  |
|  |                            |                          | ----- Angular Unconformity ----- |  |  |
|  |                            |                          | Gandikota Fm.                    | 300  | Quartzite, Shale   |
| C<br>h<br>i<br>t<br>r<br>a<br>v<br>a<br>t<br>i | Chitravati<br>Group        | Tadpatri Fm.             | 4600                             | Shale, Tuff, Quartzite, Dolomite, (Intrusives)       |  |
|  |                            |                          | Pulivendla Fm.                   | 1 - 75   | Conglomerate, Quartzite  |
|  |                            |                          | ----- Unconformity -----         |  |  |
|  |                            |                          | Vempalle Fm.                     | 1900   | Stromatolitic Dolomite, Dolomitic mudstone, Chert Breccia, Quartzite |
| P<br>a<br>p<br>a<br>g<br>h<br>n<br>i           | Papaghni<br>Group          | Gulcheru Fm.             | 28 - 210                         | Arkosic Conglomerate, Quartzite, Shale               |  |
|  |                            |                          | ----- Non-conformity -----       |  |  |
|  | Dharwar Supergroup         |                          |                                  | Gneissic, granitic complex<br>Network of Basic Dikes |  |

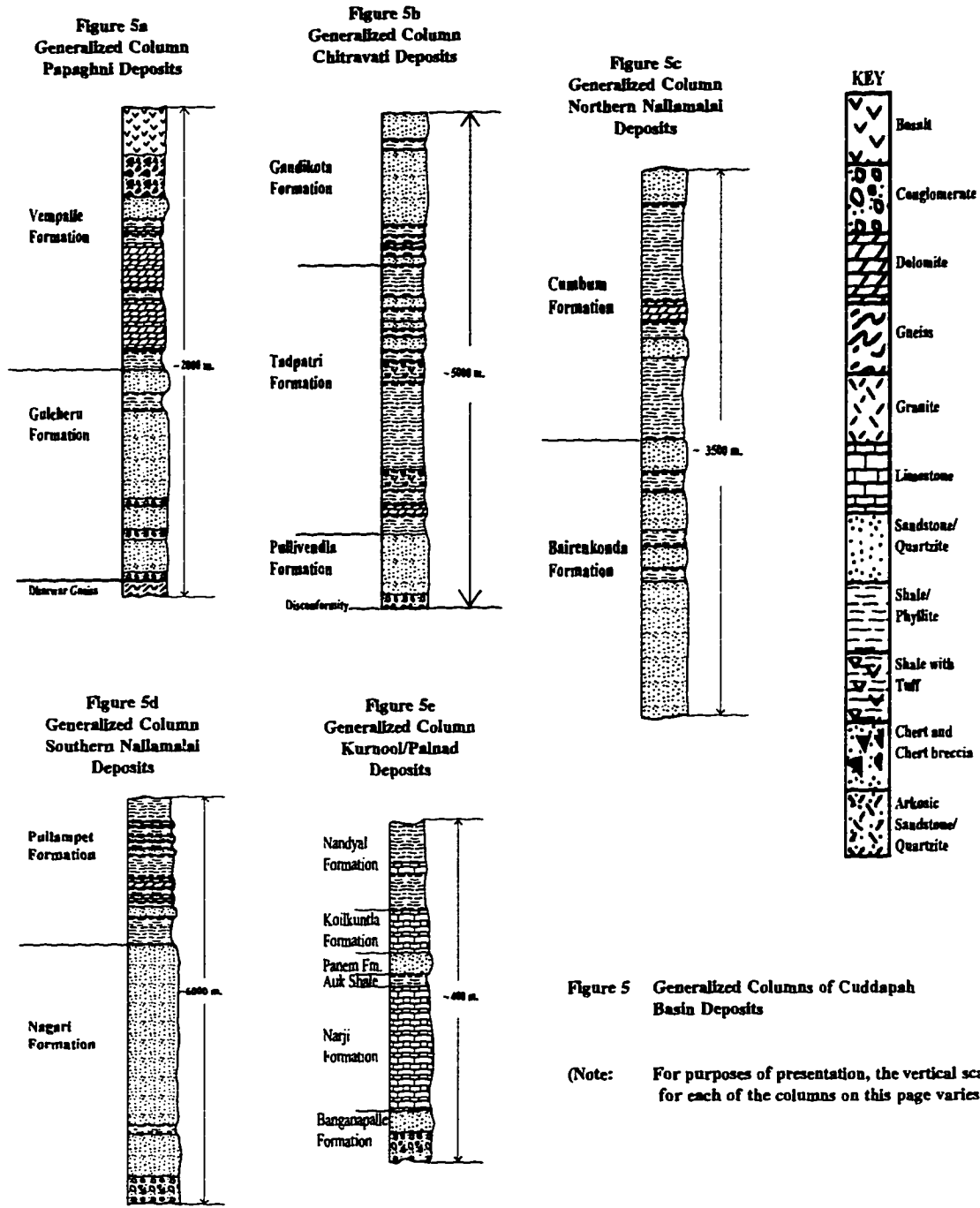


Figure 5 Generalized Columns of Cuddapah Basin Deposits

(Note: For purposes of presentation, the vertical scale for each of the columns on this page varies.)

Subramanyan (1969), reported the relative amounts of selected heavy minerals from the basal units of the sub-basins of the Cuddapah Basin as percentages of total heavy minerals. The results are summarized below:

| Mineral    | Gulcheru<br>(Base of<br>Papaghni) | Pullivendla<br>(Base of<br>Chitravati) | Bairenkonda<br>(Base of<br>Nallamalai) |
|------------|-----------------------------------|--|--|
| Zircon     | 36 - 70                           | 71 - 97                                | 87 - 96                                |
| Monazite   | 7 - 10                            | 0.8 - 6                                | -                                      |
| Tourmaline | 3 - 9                             | 0.5 - 2                                | 3 - 12                                 |
| Hornblende | 4 - 39                            | 0.5 - 4                                | trace                                  |
| Anatase    | 0.5 - 0.7                         | 3                                      | -                                      |
| Apatite    | 3                                 |  |  |

**Table 2**

Selected Heavy Mineral Concentration as Percentages of Total Heavy Minerals in Basal Unit Sediments of Cuddapah Basin Sub-basins

The relative abundances of these heavy minerals can, of course, be useful in distinguishing the different quartzites of the Cuddapah Supergroup from each other. The relative abundances of certain heavy minerals, such as zircon and hornblende, can also be indicative of the reworking of the of the sediments comprising these units. This, in turn, can aid in the determination of which sub-basin areas may have been proximate sources of sediment for other sub-basin areas. The data in Table 2 above show an increase in the concentration of heavy minerals which is consistent with a reworking of sediment from the Papaghni to the Nallamalai sub-basins of the Cuddapah Basin (Williams et al, 1982).

## Igneous Activity

Radioisotope dating of igneous rocks in and around the Cuddapah Basin, (Padmakumari and Dyal, 1987; see Table 3), as well the summaries of radioisotope dates by Bhattacharji (1987; see Table 4) and Murthy et al (1991; see table 5), indicate at least three distinct episodes or periods of magmatic activity separated by time intervals ranging from 200 million to over 300 million years.

| <b>Potassium-Argon Ages from Mafic Dike Swarms around the Cuddapah Basin</b> |   |
|--|---|
| <u>Mean Age (Ma)</u>   | <u>Episode or Group</u> (see text above). |
| 644 ± 18   | (Post Cuddapah)                           |
| 1086 ± 23  |   |
| 1084 ± 25  | 3   |
| 1124 ± 35  |   |
| 1387 ± 30  |   |
| 1486 ± 40  |   |
| 1480 ± 50  | 2   |
| 1437 ± 40  |   |
| 1518 ± 37  |   |
| 1763   |   |
| 1748 ± 35  |   |
| 1734 ± 26  | 1   |
| 1730 ± 38  |   |
| 1884 ± 40  |   |

**Table 3 Potassium-Argon Ages for Mafic Rocks in, and around the Cuddapah Basin  
(Modified from Padmakumari and Dyal, 1987)**

| Mafic Dikes   | Kimberlites    | Lamproiites    | Sills         | Extrusives      | Alkaline Syenites |
|---|----------------|----------------|---------------|-----------------|-------------------|
| <b>Post Cuddapah</b>                                    |                |                |               |                 |                   |
|   |                |                |               | 515 ± 8 (3)     |                   |
|   |                |                |               | 517 ± 8 (3)     |                   |
| (Granophyre)  |                |                |               |                 |                   |
| 640 ± 23 (3)  |                |                |               |                 |                   |
| <b>Syn-Cuddapah                      2000 - 650 Ma</b>  |                |                |               |                 |                   |
| 832 ± 40 (1)  |                |                |               |                 |                   |
| 913 ± 13 (3)  |                |                |               |                 |                   |
| 985 ± 13 (3)  | 840 ± 30 (5)   |                | 812 ± 12 (3)  |                 |                   |
| 1085 ± 15 (3)   | 1023 ± 40 to   |                | 980 ± 10 (4)  |                 | 929 ± 17 (3)      |
| 1110 ± 16 (3)   | 929 ± 18 (3)   | 1225 ± 114 (4) | 1014 ± 30 (3) | 1456 ± 20 (3)** |                   |
| 1115 ± 20 (3)   | 1150 ± 29 to   | 1319 ± 3 (3)   | 1179 ± 18 (3) | 1583 ± 147 (4)  |                   |
| 1410 ± 14 (3)   | 1350 ± 294 (5) | 1371 ± 20 (3)  | 1474 ± 53 (3) | 1588 ± 15 (3)*  |                   |
| 1480 ± 22 (3)   |                |                |               |                 |                   |
| 1497 ± 22 (3)   |                |                |               |                 |                   |
| 1653 ± 22 (3)   |                |                |               |                 |                   |
| 1732 ± 30 (3)   |                |                |               |                 | 1745 ± 20 (3)     |
| <b>Pre-Cuddapah                      2600 - 2000 Ma</b> |                |                |               |                 |                   |
| 2074 ± 34 (3)   |                |                |               |                 |                   |
| 2193 ± 45 (2)   |                |                |               |                 |                   |
| 2420 ± 246 (1)  |                |                |               |                 |                   |

\* Vempelle Basalt \*\* Tadpatri (1) Ikramudin & Stueber, 1976 (Rb - Sr ages); (2) Balasubrahmanyam, 1975 (K - Ar ages); (3) Bhattacharji & Wampler, (in preparation) (K - Ar ages); (4) Crawford & Compston, 1973 (K - Ar ages); (5) Paul et al, 1975 & Paul, 1979 (K - Ar ages and Rb - Sr ages).

**Table 4                      Radioisotope Ages of Igneous Rocks Associated with the Cuddapah Basin  
(From Bhattacharji, 1987)**

| <b>Unit</b>  | <b>Method</b> | <b>Age</b>                         | <b>Source</b>                          |
|--|---------------|------------------------------------|--|
| <b>Tadpatri<br/>(sills)</b>                        | <b>K-Ar</b>   | <b>958 +/-35Ma<br/>809 +/-29Ma</b> | <b>Murthy et al<br/>1991</b>           |
| <b>Lower<br/>Cuddapah<br/>(sills)</b>              | <b>Rb-Sr</b>  | <b>908 +/-35Ma</b>                 | <b>Crawford and<br/>Compston, 1973</b> |
| <b>Nallamalai<br/>(Mica in<br/>lamproite dike)</b> | <b>K-Ar</b>   | <b>1371 +/-45Ma</b>                | <b>Murthy et al<br/>1991</b>           |
| <b>Nallamalai<br/>(lamproite<br/>dikes)</b>        | <b>Rb-Sr</b>  | <b>1225/1140Ma</b>                 | <b>Crawford and<br/>Compston, 1973</b> |
| <b>Vempalle<br/>(metamorphosed<br/>lava)</b>       | <b>Rb-Sr</b>  | <b>1360 +/-30Ma*</b>               | <b>Crawford and<br/>Compston, 1973</b> |
| <b>Tadpatri<br/>(tuff)</b>                         | <b>K-Ar</b>   | <b>1474 +/-53Ma</b>                | <b>Murthy et al<br/>1991</b>           |
| <b>Tadpatri<br/>(tuff)</b>                         | <b>K-Ar</b>   | <b>1588 +/-53Ma</b>                | <b>Murthy et al<br/>1991</b>           |
| <b>Vempalle<br/>(lava flow)</b>                    | <b>Rb-Sr</b>  | <b>1583 +/-147Ma</b>               | <b>Crawford and<br/>Compston, 1973</b> |
| <b>Vempalle<br/>(lava flow)</b>                    | <b>K-Ar</b>   | <b>1841 +/-71Ma</b>                | <b>Murthy et al<br/>1991</b>           |

**Table 5 Radiometric Ages of Cuddapah Basin Rocks  
(From Murthy et al, 1991)  
(\* Date interpreted as a metamorphic overprint)**

**Petrographic evidence in the form of sills and dikes of mafic and ultramafic character in and around the location of the Cuddapah Basin as well as the ages of these rocks from radioisotope dating point to thermal activity originating in the mantle as a precursor of events in the evolution of the basin. Radioisotopic dates by Murthy et al (1991), Padmakumari and Dyal (1987) and Crawford and Compston (1973), (see tables 3, 4, and 5) lead to a consensus of opinion that Cuddapah Basin sedimentation began at least  $1.7 \times 10^9$  years ago and was preceded by mantle derived magmatic activity (Murthy et al, 1991; Bhattacharji, 1987).**

**Radioisotope dating of igneous rocks in and around the Cuddapah Basin as well as the structural and stratigraphic relationships of these rocks to the basin sediments, indicate mantle related magmatic activity occurred periodically throughout the evolution of the basin (Bhattacharji and Singh, 1983).**

**Sen and Narasima Rao (1967) were of the opinion that, except for the granitic rocks in the northeastern corner of the Nallamalai fold belt, the igneous rocks of the Cuddapah Basin were derived by the differentiation and/or assimilation of basic magmas from the upper mantle.**

**Viswanathan (1976) has also considered the basic igneous rocks of the Cuddapah Basin as mantle derived differentiates. He classified these rocks as belonging to one of three chemical types:**

**Type 1, no crustal assimilation, low Rb/Sr, high Ba/Rb and Ba/Sr ratios,**

**Type 2, differentiated from upper mantle, low Rb/Sr, Ba/Rb and Ba/Sr ratios,**

**Type 3, differentiated with granitic contamination, high Rb/Sr, low Ba/Rb and low Ba/Sr.**

**Nagaraja Rao et al (1987) have speculated that some "centers of eruption" for the volcanic deposits in the Cuddapah Basin may lie outside of the present limits of the basin. The author has observed in Landsat derived images extensive exposures of dikes (which is also confirmed in "ground truthing" done by many others including Murthy (1964) and Nagaraja Rao et al (1977)). They could have served as feeders for such "centers of eruption".**

**Table 6 summarizes the igneous activity affecting the sub-basins of the Cuddapah Basin. The determination of the age of these igneous rocks serves to establish the age of some of the sedimentary deposits within the sub-basins of the Cuddapah Basin.**

| <b><u>Igneous activity</u></b>  | <b><u>Age Ma</u></b> | <b><u>Sub-basin</u></b>                                |
|---|----------------------|--|
| <b>Post Cuddapah Granophyres</b>  | <b>640 to 510</b>    | <b>Nallamalai</b>                                      |
| <b>Kimberlite Dike intrusions</b>   | <b>1020 to 840</b>   | <b>Nallamalai &amp; outside of Cuddapah Basin area</b> |
| <b>Late intrusive activity, Alkaline Syenites</b>   | <b>930</b>           | <b>Nallamalai</b>                                      |
| <b>Volcanic activity in the Nagari and Cumbum Formations</b>  | <b>1220 to 1140</b>  | <b>Nallamalai</b>                                      |
| <b>Lava flows in the Vempalle Formation</b>   | <b>1800 to 1600</b>  | <b>Papaghni</b>  |
| <b>Tuffs in the Tadpatri Formation</b>  | <b>1600 to 1400</b>  | <b>Papaghni</b>  |
| <b>Pre-Cuddapah - dikes and sills in the Dharwar gneisses in the vicinity of the Cuddapah Basin</b> | <b>2400 to 2000</b>  |  |

**Table 6 Summary of Igneous Activity Affecting the Cuddapah Basin  
(Data from Murthy et al, 1991; Bhattacharji, 1987; and Padmakumari and Dyal, 1987)**

## Structure

**The Cuddapah Basin comprising the five sub-basins outlined in Figure 3, is gently tilted to the east by about 2 to five degrees (Narain, 1987).**

**The intensity and complexity of post depositional deformation varies considerably within the basin. The western part of the Cuddapah Basin is not significantly deformed and the oldest sedimentary units, (i. e. the Papaghni), lie unconformably, and relatively undisturbed, on the eroded surface of the Archean basement rocks of the Dharwar Supergroup. To the east, beyond the lineament separating the area of Papaghni and Chitravati sedimentation from the Nallamalai, the amplitude of folding increases, ending with tight, isoclinal to overturned folds in the east, known as the Nallamalai fold belt (see Figure 4). The eastern margin of the basin is truncated by overthrust faults such as the Eastern Border fault (Vellikonda Thrust Front) generally believed to be related to the Pan-African Orogeny in which the Archean basement rocks of the Dharwar Supergroup are thrust over the Proterozoic Nallamalai deposits (Dutt, 1962; Rao et al, 1987).**

**The stratigraphic evidence discussed earlier shows that the Palnad and Kurnool sub-basins are superposed over the older Papaghni, Nallamalai and Srisailam sub-basin areas. The early stages in the evolution of the Cuddapah Basin are contained within these older sub-basin areas which appear to be bounded and separated from one another by major lineaments as shown in Figure 4. These**

lineaments are described by Kaila et al (1979, 1990) as deep seated faults or fractures.

The compass rose diagram in Figure 4 shows that the major lineaments are well represented in the vicinity of the Cuddapah Basin. The Proterozoic basins on the Indian Shield are apparently located at the intersections of these lineaments (see Figure 1). However there are two other prominent sets of lineament orientations appearing in the compass rose diagram of Figure 4 that are interpreted here as a conjugate shear set related to the stresses imposed by collision tectonics synchronous with the folding of the Nallamalai sub-basin deposits. The offset of other structures within the basin along some of these faults indicates that they were reactivated late in the evolution of the basin (see Figure 4).

In shape, the Cuddapah Basin is asymmetrical, about the oldest part of the basin (i. e. the Papaghni sub-basin; see Figures 4 and 6). It has been suggested by Bhattacharji (1981), Kaila et al (1979), and by Nagaraja Rao et al (1977), that this asymmetry, in part due to the tilting of the basin with respect to the present, eroded surface, may be further influenced by pre-existing zones of weakness (i. e. deep faults or fractures) in the lithosphere. It has been further suggested by Nagaraja Rao et al (1987) that zones of weakness marked at the surface by large scale lineaments may also control the shape of the basin, in that they control the lateral limits of subsidence in the basin (see Figures 4, and 6).

**The Srisailam Lineament and the Kalva fault separate the area of the Srisailam sub-basin from that of the Nallamalai and the Papaghni sub-basins. (see Figures 4 and 6.)**

**The Papaghni and the Nallamalai sub-basins are separated by a lineament which, is obscured at the present time due to the overlying Kurnool sediments, but which appears in Landsat imagery to extend beyond the boundaries of the Cuddapah Basin and is seen in the surrounding Archean rocks of the Dharwar Supergroup (see Plate 1).**

**The southern tip of the Nallamalai sub-basin as well as the Eastern Border fault (Vellikonda Thrust Front) is truncated and offset by the Karkambad fault at Tirupati (see Figures 4 and 6).**

**The Palnad and the Kurnool sub-basins have a tectonic (fault) contact with the Srisailam Plateau which lies between them and transgressive stratigraphic (unconformable) contacts with the older Cuddapah Basin sediments to the northeast and southwest respectively. Thus, it appears that the Srisailam Plateau is on a horst bounded by half grabens on either side upon which the Kurnool and Palnad sub-basins which are located (see Figure 7c).**

**There are at least three major domal structures within the Nallamalai fold belt (see Figures 4 and 6b) including the Iswarakuppam Dome which lies along the line of the cross section in Figure 6b. King (1872) considered these as supratenuous**

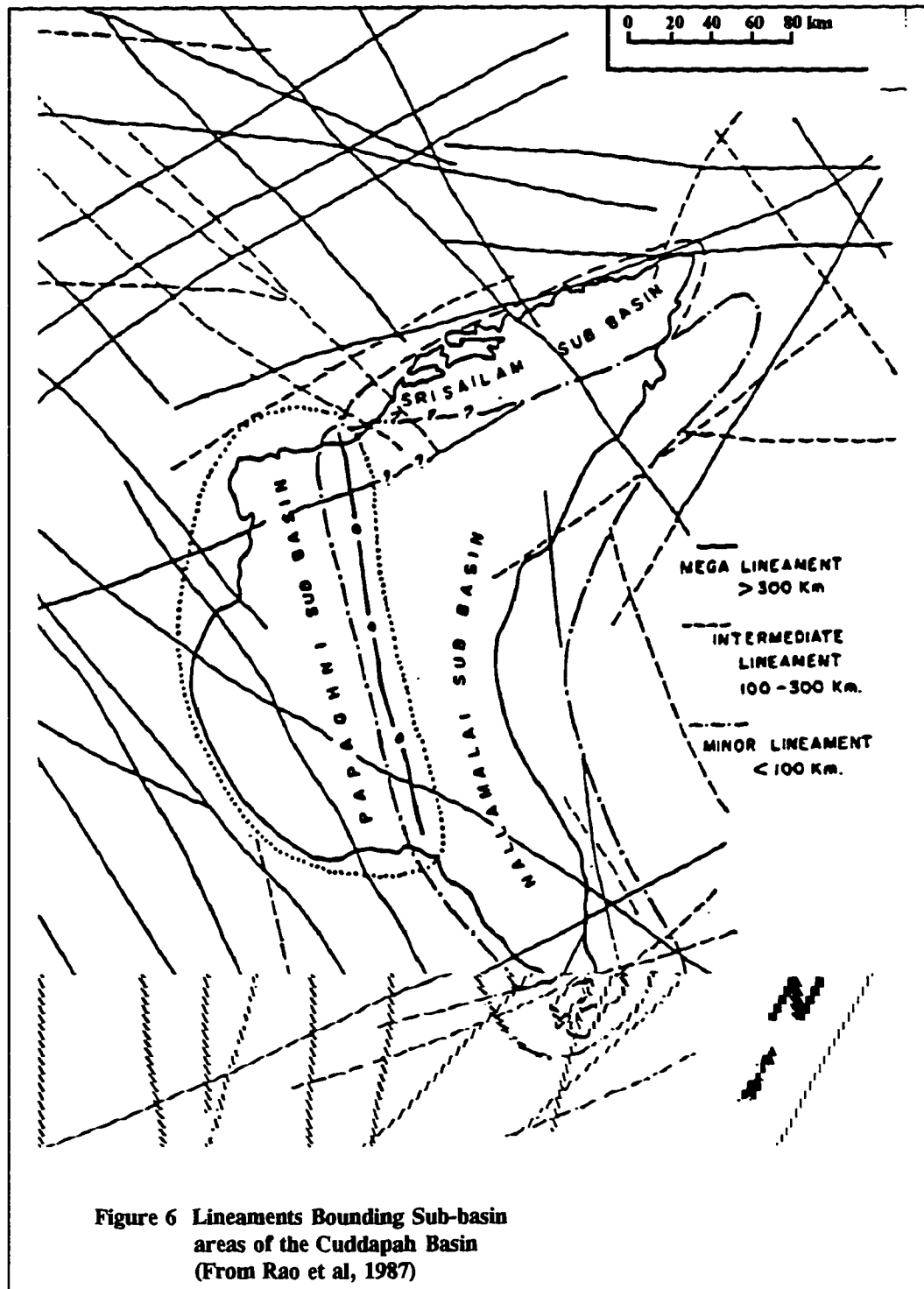
**folds over topographic highs on the basement. However, the orientation of the fold axes of the Iswarakuppam Dome does not support this interpretation (see Figure 4). Nor is there convincing evidence that these domes are due to fold interference. Because of the presence of younger granitic rocks in the cores of some of these domes, it seems more reasonable that these domes are the result of the upward movement of remobilized granitic basement material subsequent to the formation of the Cuddapah Basin (Nagaraja Rao et al, 1987).**

**Other major structures associated with the Cuddapah Basin include the following faults:**

**The Kalva Fault is also known as the Ramallakota-Gani-Kalva Fault. This fault has as a surface expression a steep monoclinial feature known as the "Kalva wall". This fault extends through the basement, but the fact that it affects the younger Kurnool deposits is an indication that it has been reactivated in post-Kurnool times (Coulson, 1933; see Figure 4).**

**The Atmakuru fault, which separates the Srisailam Plateau from the Kurnool sub-basin (see Figure 4).**

**En echelon thrust faults which occur along the western boundary of the Nallamalai sub-basin (also known as the Vamikonda Thrust Front). These represent Nallamalai rocks thrust over the older Papaghni and Chitravati rocks to the west of the Nallamalai sub-basin (see Figure 4).**



**Fig. 7a**

**Fig. 7b**

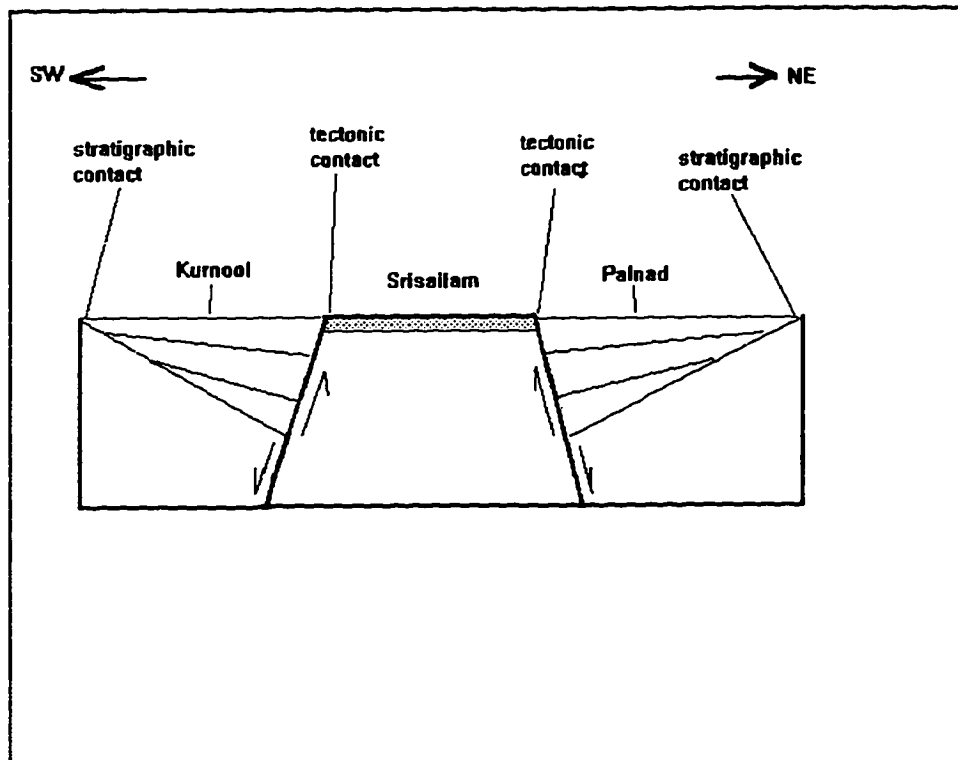


Figure 7c Structural Relationship of Srisailam to Kurnool and Palnad Sub-basins (See figure 3 for section location.) (Note: This figure is a schematic representation, not drawn to Scale.)

The northern end of the Nallamalai sub-basin is bounded by the Srisailam lineament. The offset of the Palnad deposits as well as that of the eastern border fault at the northeastern boundary of the Cuddapah Basin along the Srisailam Lineament indicates post-Kurnool reactivation along this lineament. This was possibly synchronous with that of the Kalva Fault (see Figure 4).

**The Idupulaya fault forms the southern boundary of the western Cuddapah Basin (see Figure 4).**

**The Karkambad fault and the Ramallakota-Gani-Kalva fault extended along the Srisailam lineament are interpreted here as parallel faults showing a left-lateral, (i. e. sinistral) strike-slip component (Figure 4).**

**The major deep seated faults which bound the sub-basins of the Cuddapah Basin have been reactivated during the evolution of the basin and as discussed above, during post-Kurnool times. However these faults appear to have been present in the Archean crust prior to the development of the Cuddapah Basin (Nagaraja Rao et al, 1987).**

## Models for Basin Evolution

There are essentially three types of crustal stress environments which are conducive to the creation and evolution of sedimentary basins. Those in which the direction of maximum stress is vertical (i. e. extensional basins), those in which the direction of maximum stress is horizontal and the direction of minimum stress is vertical (i. e. compressional or convergent basins), and those in which the direction of maximum stress is horizontal and the direction of minimum stress is also horizontal (i. e. shear or "pull-apart" basins) (Miall, 1990; see Figure 8).

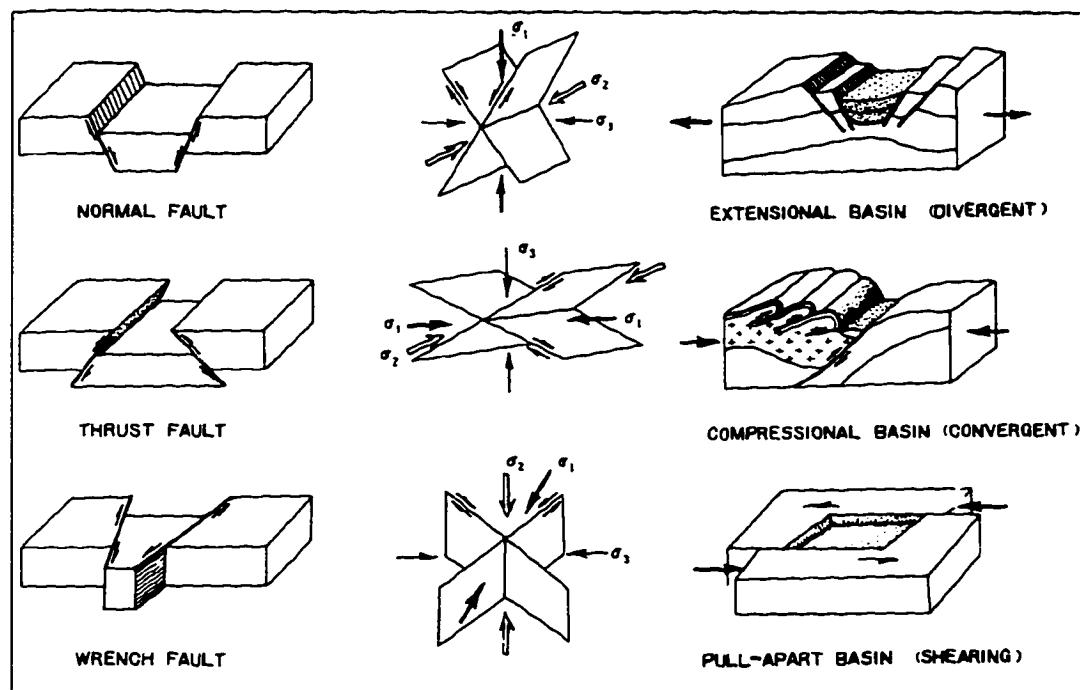


Figure 8. Basin Types (from Liu Hefu, 1986)

**Prior to the general acceptance of plate tectonic theory, sedimentary basins were explained and classified on the basis of geosynclinal theory (Kay, 1951). These interpretations were descriptive in detail, but lacked an adequate explanation of the mechanisms of basin subsidence and filling. In the past twenty five years the terminology based on geosynclinal theory has been generally abandoned by geologists in favor of a new terminology based on the mechanics of plate movements and interactions (Miall, 1990).**

**In addition to structural origin (see Figure 7), basins can be further classified in other ways. Miall (1990) has suggested using the following criteria for basin classification:**

- 1. The nature of the basement underlying the basin.**
- 2. The location of the basin relative to plate margins during its evolution.**
- 3. The nature of the lithospheric interactions which have affected the sedimentation into the basin.**

**Applying these criteria, the author believes that the Cuddapah Basin should be classified as an intracratonic basin for the following reasons:**

- 1. The Cuddapah Basin lies on Archean crust as do the other Proterozoic basins on the Indian Shield. There is no evidence, at least in the Archean Indian crust of collision type tectonic events contemporaneous with the initial formation of these basins. However there is evidence**

**of collision tectonics subsequent to the formation of the basins (Salop 1983; Rao et al, 1987) (see argument number 4 below).**

- 2. The Proterozoic basins of the Indian Shield are located, and bounded by, the intersections of large scale lineaments, which represent deep, high angle lithospheric fractures (Kaila et al, 1979).**
- 3. Some workers (e. g. Salop, 1983) refer to the Cuddapah Basin as an aulacogen (failed rift). However the nature of the fractures bounding this, and the other Proterozoic basins of the Indian Shield, as well as its spatial relationship to the other Proterozoic basins on the Indian Shield, (i. e. their locations at the intersections of several sets of major lineaments), do not support this interpretation. There is no indication that there are triple junctions of Proterozoic age, associated with this basin or the other Proterozoic basins on the South Indian shield (see Figure 4).**
- 4. Prasad et al (1987) consider the Cuddapah Basin as a "Proterozoic analog" of a Himalayan type fore-deep basin. According to them, the basin originated in collision tectonics related to the Pan-African orogeny. This does not necessarily exclude the possibility of a thermal event related to a mantle perturbation or meteorite impact, resulting, ultimately, in the subsidence of the Papaghni sub-basin. However, the**

timing of the events in the evolution of the Cuddapah Basin, derived from the dates obtained for magmatic activity within the basin, (Padmakumari and Dayal, 1987; Murthy et al 1991) and from the stratigraphy (Rao et al, 1987), does not support the idea of a collision tectonic type of event such as the Pan-African Orogeny as being the initial cause of the development of the Cuddapah Basin. Rather the evidence supports a collision tectonic event possibly related to the Pan African Orogeny, as being the closing event in the evolution of the Cuddapah Basin, (op. cit.).

5. Krishna Brahman et al (1985) have suggested a large meteorite impact at about 1700 m. y. ago as the initiating event in the formation of the Papaghni sub-basin in the south-western portion of the Cuddapah Basin, rather than the mantle perturbation suggested by Bhattacharji (1981). However, there is no clear evidence, in and around the Cuddapah Basin, of the impact related structures that would be expected following such an event. Inspection of the orientation of mafic dikes around the Cuddapah Basin, as reported by (Murthy et al, 1991) and as indicated in Landsat derived images shows such orientation to be inconsistent with meteorite impact as a causative event, in that they are not oriented radially with respect to the center

of the basin (see Figure 4; Plate 1).

One of the critical questions having to do with intracratonic basin development and evolution is the so called "space problem". This can be stated simply as follows: By what mechanism, or mechanisms, the space for the deposition of sediments in an intracratonic basin is created?

Whatever the initiating process may be, once a depressed area is created on the surface of a craton it will fill with water and receive sediments derived from the surrounding area. According to the Airy model, subsidence would occur due to loading of the basin floor by sediments that are of greater density than the water in the basin that they displace. Subsidence creates additional space for the deposition of sediment. Subsidence and sedimentation would continue until isostatic equilibrium is established (Jefferies, 1962).

The thickness of sediment due to sediment loading and isostatic adjustment is given by:

$$A = h(\rho_m - \rho_w)(\rho_m - \rho_s)^{-1}$$

Where;      A = thickness of sediment (maximum)  
                   $\rho_m$  = mantle density  
                   $\rho_w$  = water density  
                   $\rho_s$  = sediment density  
                  h = water depth

(after Jefferies, 1962).

The maximum thickness of sediment observed in the Cuddapah Basin is about 12 km (Nagaraja Rao et al, 1987). It has long been recognized that basin floor subsidence due only to isostatic adjustment to sedimentation into the basin is not sufficient to explain the thicknesses of sediment observed in the Cuddapah Basin (Bhattacharji, 1981). Bhattacharji and Singh (1983) have suggested a "thermal driving load" as a mechanism to account for the excess subsidence and sedimentation.

McKenzie (1978) considered the thermal consequences of crustal thinning. He showed that thinning, by whatever mechanism it occurs, causes an increase in the thermal gradient in the thinned area. If the crust above the thinned area is thin enough, the redistribution of heat would result in an initial uplift at the surface due to thermal expansion of the crustal rocks. As the equilibrium thermal gradient is reestablished, cooling of the subcrustal rocks would result in contraction and a consequent subsidence.

The McKenzie theory is illustrated in Figure 9. A segment of lithosphere with an initial horizontal dimension  $a$  is extended by a factor equal to  $\beta$ . The resulting horizontal dimension would be equal to  $\beta a$ . The thickness of the same lithospheric segment is decreased by the factor  $1/\beta$  (assuming that volume is maintained). Where  $\beta$  is a number greater than 1. The higher temperature asthenosphere is now closer to the surface giving an increased geothermal gradient.

As indicated above, reestablishment of the geothermal gradient causes contraction and subsidence. This mechanism has been termed "Pratt subsidence". Gravitational loading by the sediment deposited in the basin thus created would result in additional subsidence due to isostatic adjustment.

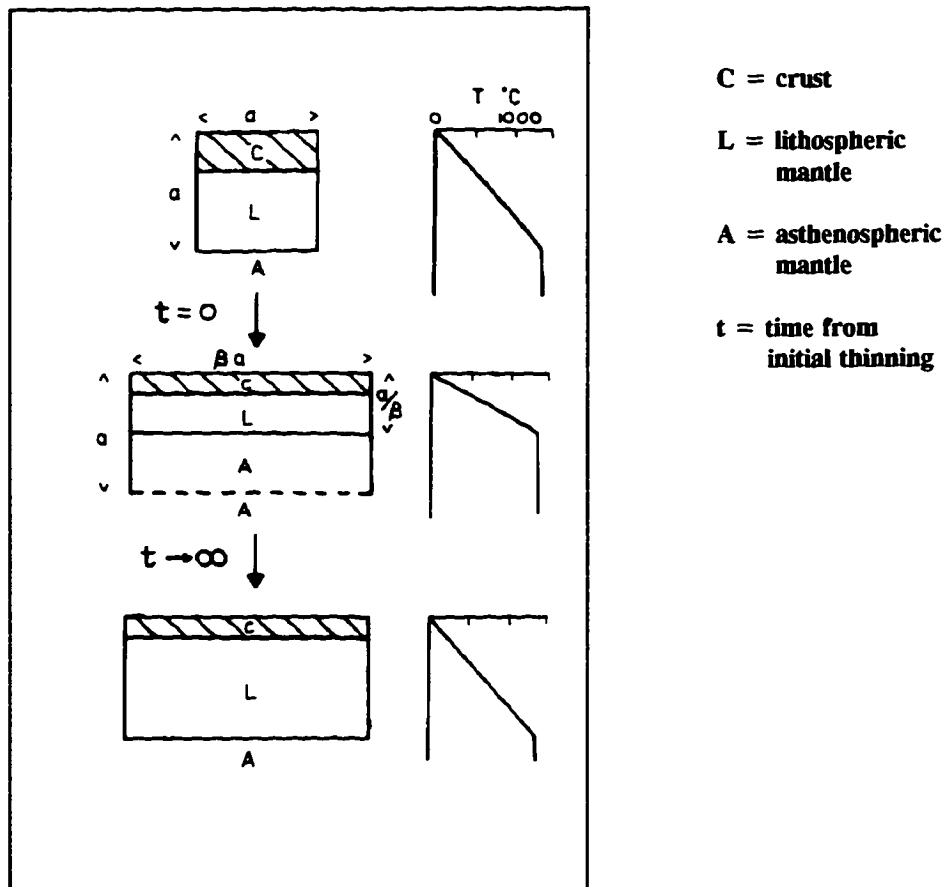


Figure 9. McKenzie Theory of Origin of Basins by Crustal Thinning (From Miall, 1990)

Values of  $\beta$  average  $\leq 2$  for most intracontinental basins (Miall, 1990) but for basins such as the Cuddapah Basin where there has been significant igneous dike activity this value can be much greater (Dewey, 1982; Royden et al, 1980).

Watts (1981; 1982) considered the effects of a progressive increase in the rigidity of the lithosphere with cooling and showed that the result would be a progressive coastal onlap or transgressive extension. Where such extension occurs symmetrically about a center of subsidence, as in McKenzie's (1978) "Pure Shear" model, the result would be the classic "longhorn" or "steer's head" basin geometry (see Figure 10).

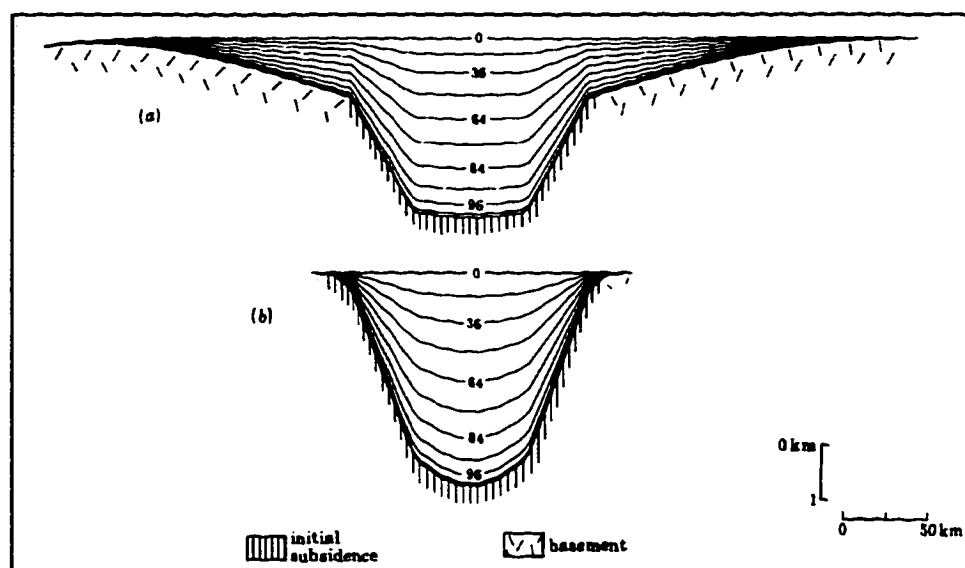


Figure 10, "Steer's Head" basin geometry (From Watts, et al, 1982)

In case (a) above, the lithosphere is considered to behave elastically with no significant thermal relaxation. In case (b), the lithosphere is considered to be viscoelastic with thermal relaxation effecting a significant "decoupling" of the vertical load in the center of the basin with the surrounding lithosphere. This results in a narrower deeper basin. It should be noted that, although it is highly temperature dependent for typical lithospheric conditions, the effects of thermal relaxation are not significant for periods of time less than about  $10^7$  years (Beaumont, 1981).

Royden et al (1980) considered the difference between the rheological properties of the crust (upper lithosphere) and the lower lithosphere (upper mantle), showing that the crust would yield in a brittle manner while the mantle lithosphere would yield in a more ductile fashion (Artemjev and Artyushkov, 1971). This "two layer" model of the lithosphere means that there would be different amounts of extension in the crust and mantle for a particular stress condition. Wernicke (1985) attempted to resolve this problem for the Basin and Range province of North America. He proposed the simple shear model for lithospheric extension as contrasted to the symmetrical pure shear model of McKenzie. In the pure shear model, the crustal extension is assumed to take place directly above the extension of the lithospheric mantle.

In Wernicke's simple shear model, the extension of the lithosphere is separated into a "proximal" portion occurring in the crust and a "distal" portion occurring in the mantle and offset horizontally from the proximal extension of the crust (see Figure 11).

Royden et al (1980) showed that for many basin environments the intrusion of mantle derived material into the crust early in the development of a basin can significantly affect basin evolution. The presence of this dense mafic and ultramafic material in the crust can by itself account for considerable basin subsidence and mantle related magmatic activity

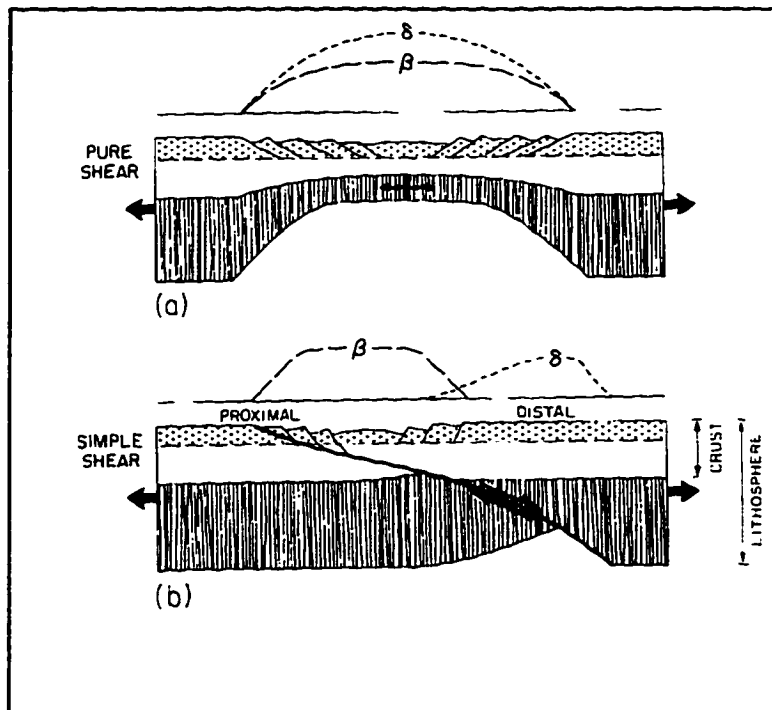


Figure 11. Pure Shear (McKenzie model) vs. Simple Shear (Wernicke model) (Modified from Miall, 1990)

may, in fact, be the initiating event in the formation of basins such as the Cuddapah Basin (Bhattacharji, 1987).

Artyushkov (1992) showed that both short and long term high amplitude

subsidence can be induced by mantle related magmatic activity which results in an increase in the density of the upper lithosphere independently of the effects of crustal thinning due to extension. This is particularly relevant to the case of the Cuddapah Basin in which crustal extension sufficient to produce the observed thickness of sediment by crustal thinning and thermal relaxation, has not been demonstrated. In some cases thermal effects may be superimposed upon the effects of crustal extension.

The thermal hypotheses constitute one of three major approaches to this problem developed by workers in the field in recent years. The other approaches consist of hypotheses involving the reaction of the lithosphere to horizontal stresses (compressional, tensional or shear, i. e. mechanical models relating to collision tectonics.) the reaction of the lithosphere to gravity loading and unloading or some combination of these effects (eg. thermo-mechanical models). It is to be noted that these mechanisms are not mutually exclusive, and it is suggested that all may be operative to a greater or lesser degree in any particular case of basin evolution.

Sleep (1971) is primarily responsible for much of the early development of the thermal model for basin evolution. He proposed that heating of the upper lithosphere causes thermal expansion, a reduction in density and consequent isostatic uplift. Erosion of the upper surface of the uplifted crustal material would provide the space necessary for the deposition of basin sediments after the cooling,

**contraction and subsidence of this uplifted material.**

**According to Sleep's (1971) model, subsidence would follow an exponential cooling curve with time. Studies by Keen (1979) of continental margins (i. e. rifted marginal basins) have tended to confirm this hypothesis. Some intracratonic basins, such as the North American Michigan and Williston Basins do not show evidence of an initiating thermal event. However the Cuddapah Basin clearly shows such evidence in the form of magmatic activity indicated by mafic and ultramafic dike swarms in the Archean basement around the basin as well as intrusives and extrusives within the basin (Murthy et al, 1991; Rao et al, 1987). In addition there is geophysical evidence (gravity studies) for a body of dense mantle-derived material having intruded the lithosphere beneath the Cuddapah Basin (Tewari and Rao, 1987; 1990).**

**Bhattacharji (1984; 1986) has suggested that extension and/or thinning may take place at pre-existing "weak zones" in the lithosphere which may be represented by lineaments at the surface. Bhattacharji, (personal communication) has further suggested that the location of the surface effects of an initiating thermal event, such as a mantle perturbation, could be controlled to some extent by the location and configuration of these pre-existing zones of lithospheric weakness. Stratigraphic, petrographic and geophysical evidence (Rao et al, 1987; Bhattacharji, 1981) suggest that the uplift of the Papaghni sub-basin was due to an initiating thermal event (i.e.**

**a mantle plume) under the area of the Papaghni sub-basin.**

**Previous work by others (Haxby, 1976; Sleep, 1971) indicates that the response of the crust to such a thermal event would be rapid initial uplift at the surface. This would be due to expansion of plume material melting as it approaches the surface, the heating and consequent expansion of the "country" rocks, and the buoyancy of the plume itself. Such a thermal event could result in crustal thinning by erosion of uplifted rocks by extensional faulting in the uplifted crustal rocks, by viscoelastic stretching and/or by gravity tectonics (i. e. gravity sliding) during the uplift phase. This would then be followed by a slower subsidence phase due to cooling and contraction of rocks below the surface of the basin, crystallization of magma under the basin, and the transfer of magma from beneath the basin to the surface (see Figure 12). This subsidence provides the space necessary for the deposition of sediments. Isostatic adjustment to loading by sedimentation into the basin would cause additional subsidence.**

**Considering the Cuddapah Basin as a whole, it becomes apparent that the timing of any lateral thermal effects due to a mantle perturbation would be significantly delayed from the timing of the thermal effects immediately above the plume. The time necessary for the conduction of heat through rock is a function of the square of the distance through which the heat is conducted. Verhoogen et al (1970) argue that it would take  $3 \times 10^8$  years for heat to be conducted through 100**

km of typical crystalline rock. Assuming a typical thermal diffusivity of  $0.01 \text{ cm}^2/\text{sec.}$ , for crystalline rock (Verhoogen et al, 1970) this model predicts a time of approximately  $4 \times 10^8$  years for the same effect over the same distance (see Figure 13). If one considers that the center of the Nallamalai sub-basin is 70 to 75 km from the center of the Papaghni or about 30 km from the nearest boundary of an intrusive body 80 km in diameter, it should take about  $5 \times 10^6$  years for the thermal effect (i. e. a change in rock volume beneath the basin, due to heating) from a mantle intrusion under the area of the Papaghni sub-basin to begin at the center of the Nallamalai sub basin. The time interval from a single event of emplacement of mantle derived material to the maximum thermal effect on the Nallamalai sub-basin would clearly be much greater.

The magnitude of the thermal effects at any given location is a function of the dimensions of the basin, the thermo-mechanical properties of the rocks, and the distances. These, as well as the timing of these effects, are considered in this study. This study goes beyond those of Sleep (1971) and Haxby and Turcott (1976) in that boundaries and the timing of lateral thermal effects are considered.

The Cuddapah Basin demonstrates a history of magmatic, tectonic, erosional and depositional activity that spans a period that is estimated to be from 700 million years (Salop, 1983) to about a billion years (Murthy et al, 1991; Rao et al, 1987).

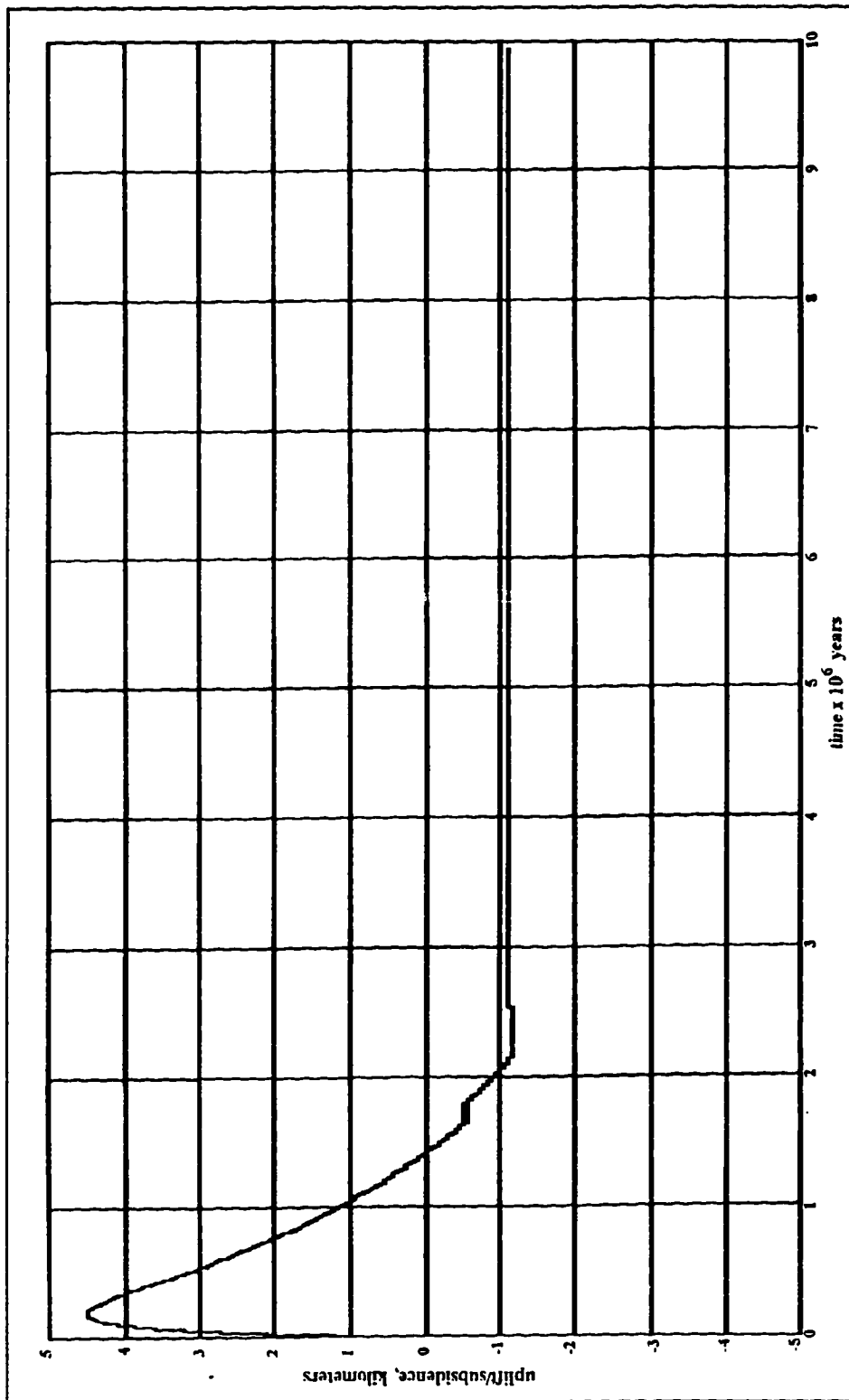
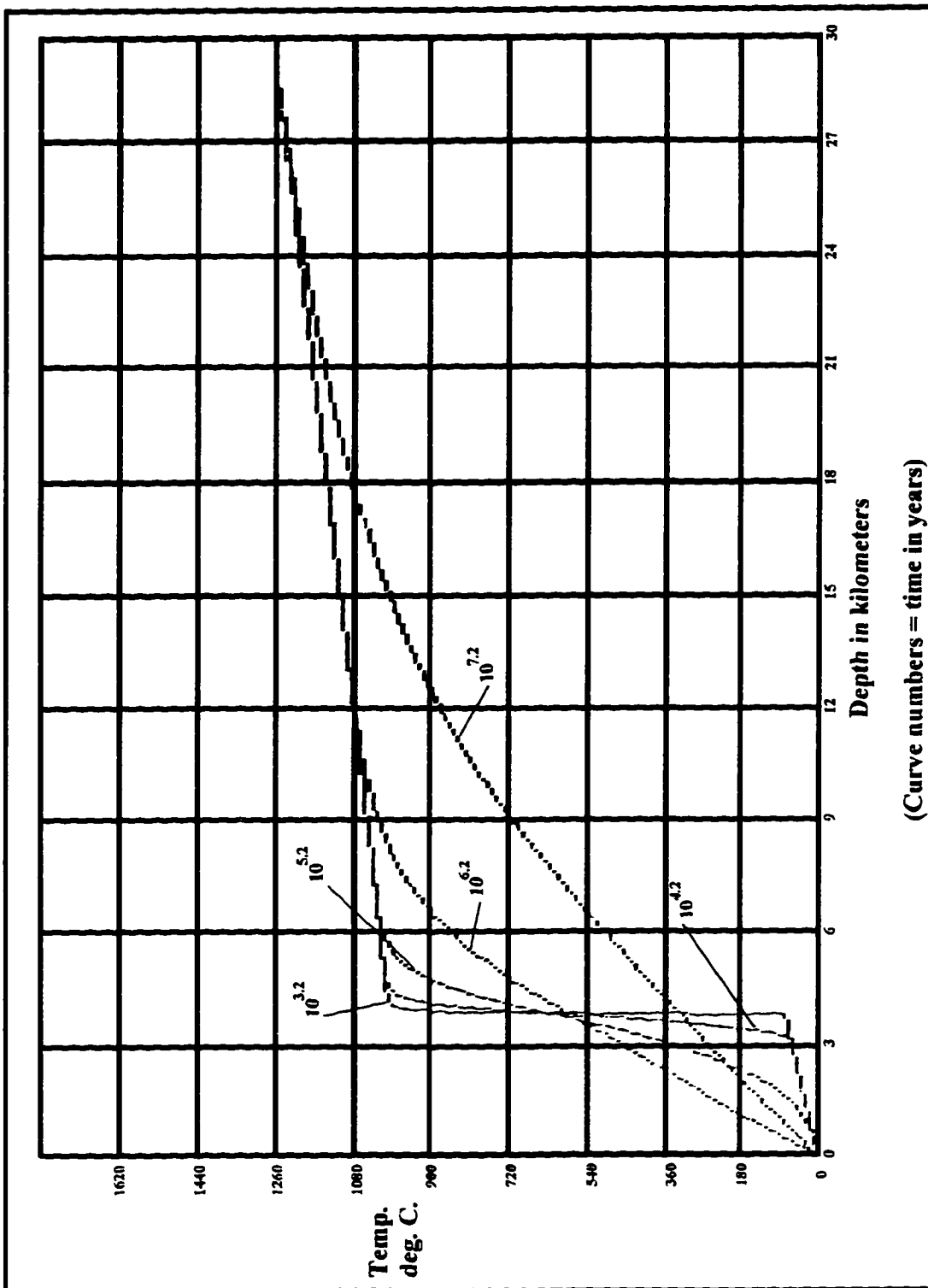


Figure 12 Computer simulation of uplift and subsidence of the surface above a mantle plume, plume temperature = 1400°C. Initial depth to plume = 7 km.

**There is considerable evidence (Nagaraja Rao, 1987) that during the long history of the Cuddapah Basin some of the sub-basins (i. e. the Papaghni, the Nallamalai and the Srisailam) have moved vertically with respect to one another (Rao et al 1987). Bhattacharji (1987) has postulated asthenospheric upwellings as a driving mechanism for these vertical movements, the initial one ultimately taking the form of a lopolithic cupola under the Papaghni sub-basin. Gravity and magnetic studies of the Cuddapah Basin (Tewari and Rao, 1987; 1990) tend to support this hypothesis. These studies have provided information about the size, shape and depth of this dense presumably mantle-derived material (op. cit.).**

**Rao et al, 1987), considered both the Nallamalai and the Srisailam as yoked basins, the subsidence of which was consequent on the uplift of adjacent areas. That is, the subsidence of one sub-basin occurs upon the uplift of an adjacent sub-basin, which then becomes the source area of the sediments deposited into the subsiding sub-basin. The sediment removed from the uplifted sub-basin unloads it, causing further uplift by isostatic adjustment. The sediment deposited into the subsiding sub-basin loads it, causing increased subsidence by isostatic adjustment.**



Heating of overlying rocks by a large tabular body  
(Curve numbers = time in years)

Figure 13

**The author agrees that the evidence available and cited earlier tends to support this concept of the yoking of the sub-basins within the Cuddapah Basin. It is consistent with the structure and lithostratigraphy of the basin. The composition of the lithic sediment filling the Nallamalai sub-basin, particularly the basal material, directly east, and adjacent to the Papaghni, indicates an uplifted Papaghni as a source area (Rao et al, 1987). Since the Papaghni sub-basin contains the oldest sediments this shows a change in the vertical position of these sub-basin areas relative to each other. The increasing sediment loading within the Nallamalai apparently causing an eastward migration of the area of deposition and subsidence within the Nallamalai sub-basin (op. cit.). The yoking mechanism also accounts for the evident reworking of sediment from the older to the younger Cuddapah sub-basins (see Table 2).**

## **Investigative Procedure**

**Earth satellite imagery (Landsat, infra-red bands) covering the area of the Cuddapah Basin and environs is used to delineate hypothetical "decoupled blocks" within the basin (see plate 1). This is an overlay on a mosaic of enhanced Landsat MSS images. These images were enhanced by sharpening and by contrast and density adjustments so as to better define lineations in the area of the exposed Dharwar Archean basement rocks as well as within the Cuddapah Basin itself. The overlay shows the lineations that represent lineaments around and in the basin area.**

**Based upon analyses such as those reported by Balakrishna (1981) (after Kalia et al, 1979), and by Tewari and Rao (1990) from deep seismic sounding (DSS) profiles, the author considers that these lineaments correlate to deep seated, high angle lithospheric fractures or faults (see Figures 4, 6 and 14). Please note that, as there is no vertical exaggeration shown in the DSS profile, these faults or fractures are interpreted as being nearly vertical.**

**As shown in Figures 4, 6 and Plate 1 the older sub-basins of the Cuddapah Basin (excluding the superposed Kurnool and Palnad sub-basins) are bounded and separated from each other by lineaments and therefore by deep seated, high angle fractures or faults. It is further hypothesized that these discontinuities represent zones of weakness along which the vertical movements of the sub-basins relative to one another have taken place. If this is the case, then the effect of "decoupling" at**

**the zones of weakness (i. e. the deep seated fractures) would cause the nature of the subsidence in the sub-basins to more closely approximate case (b) in Figure 10 than case (a). All other things being equal, this results in a deeper basin than that which would occur if the sub-basin were not mechanically decoupled from the surrounding area (Watts et al, 1982).**

**The sub-basin areas are therefore considered to be overlying "stress decoupled blocks" for the purposes of this study (see Figures 4, 6, 14 and Plate 1).**

**The center of the Papaghni Sub-basin is located at the intersection of two such "mega-lineaments" (see Figure 6). This would support the idea suggested by Bhattacharji (1987), that the emplacement of mantle plumes into the crust is, to some extent, controlled by pre-existing lithospheric weaknesses, such as faults or fractures.**

**The purpose of the computer model simulations is to determine if under geologically reasonable conditions a mantle perturbation or plume could account for the observed thickness of sediments in the Cuddapah Basin and other similar basins, and to help constrain possible mechanisms for the relative vertical movements of the Papaghni, Nallamalai, and the Srisailam sub-basins. These simulations also demonstrate the period of time over which a single perturbation or plume, of a given size and initial temperature, could reasonably be expected to affect (i. e. cause significant tectonic activity within) the Cuddapah Basin or similar basins.**

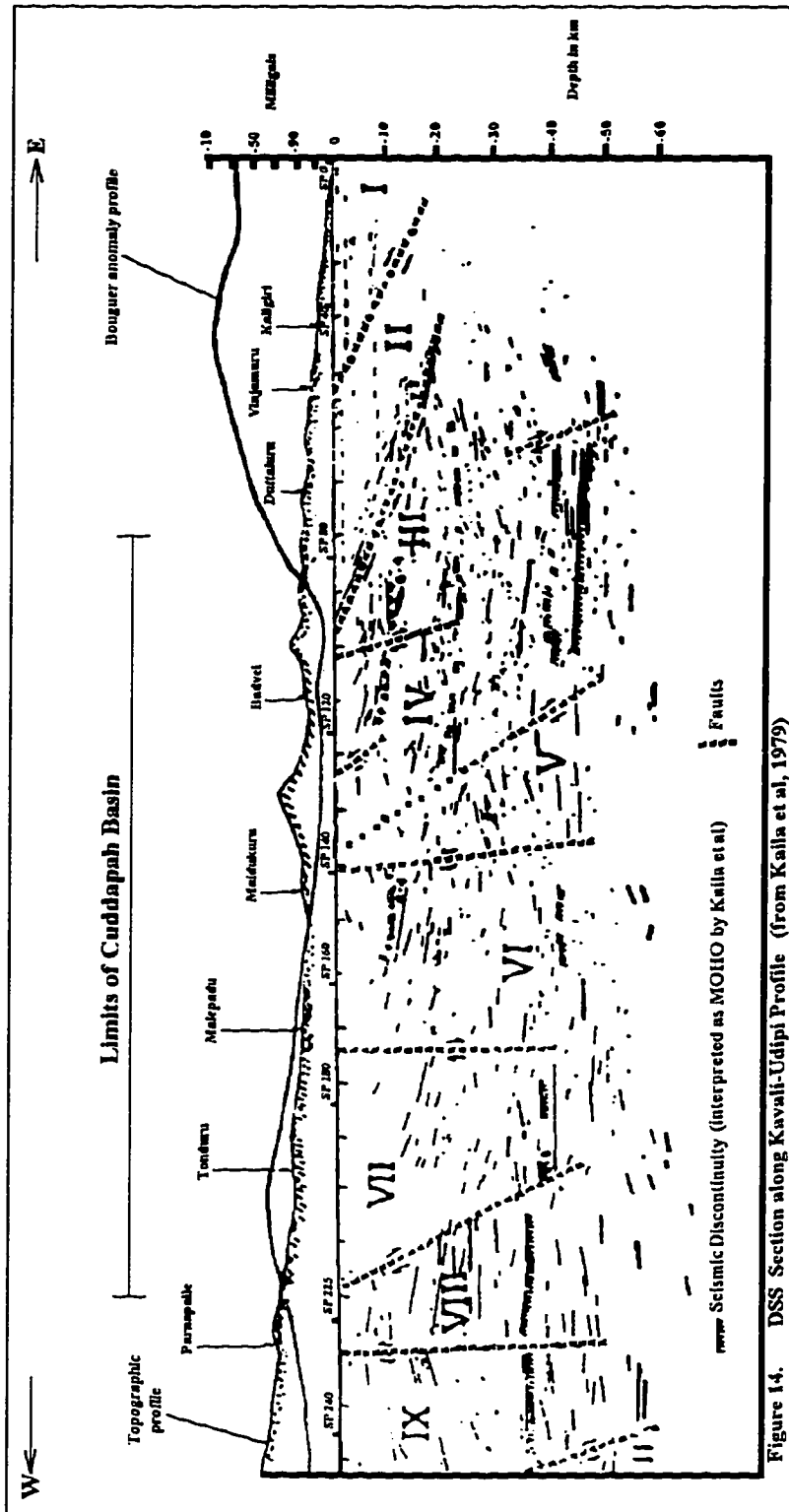


Figure 14. DSS Section along Kavali-Udipi Profile (from Kaila et al, 1979)

**The algorithms for the computer simulations are as follows:**

$$T_{(n+1)(i)} = T_{(n)(i)} + \mu dt [T_{(n)(i-1)} + T_{(n)(i+1)} + 2T_{(n)(i)}]$$

**and (for 3 dimensions);**

$$T_{(n+1)(i,j,k)} = T_{(n)(i,j,k)} + \mu dt [T_{(n)(i,j,k)}] / (dl)^2$$

**Where; T = temperature**

**$\mu$  = thermal diffusivity**

**dt = time integration interval**

**n = iteration number**

**i, j, and k = spatial node numbers**

**dl = nodal interval = distance between nodes**

**and;**

$$[T_{(n)(i,j,k)}] = T_{(n)(i+1,j,k)} + T_{(n)(i-1,j,k)} + T_{(n)(i,j+1,k)} + T_{(n)(i,j-1,k)} + T_{(n)(i,j,k+1)} + T_{(n)(i,j,k-1)} - 6T_{(n)(i,j,k)}$$

**These algorithms were modified from a finite difference approximation technique used for analogous groundwater potential as described by Wang and Anderson (1982). The output of these simulations consists of graphs of basin subsidence with time and graphs of temperature distribution with distance from a body of magma for different time intervals after the initial intrusion (Appendix 3).**

**For the explicit approximation to be stable,  $\mu dt / (dl)^2$  must be equal to, or less than 0.5 (Wang and Anderson, (1982)). For this model simulation,  $\mu dt / (dl)^2$  was**

set to 0.5, thereby determining the time integration interval,  $dt$ , to be approximately  $1.6 \times 10^2$  years.

$$dt = 0.5 (dl)^2/\mu = 0.5 (104 \text{ cm})^2/(0.01 \text{ cm}^2/\text{sec}) = 1.6 \times 10^2 \text{ years}$$

The preceding algorithms essentially simulate by finite difference approximation the technique first described by Lovering (1935 and 1955) which were applied to approximately tabular, cylindrical and compact spherical intrusions. The simulations of uplift and subsidence used in this study however address melting and crystallization, and the thermal characteristics of different rock types.

Figures 15 and 16 show the distribution of heat from hypothetical compact magmatic intrusive bodies, of spherical and cylindrical shape at selected time intervals after initial intrusion. It appears that for compact roughly spherically shaped bodies, the time interval to maximum heating of a given volume of rock by conduction is about an order of magnitude greater than the time interval to initial heating, for points near, (i. e. within a distance from the body of two times the diameter of the body or less), the intrusive body.

The model simulations were run using programs written by the author in the Basic programming language and then compiled to machine language executable files using a Microsoft Quick Basic version 4.5 editor and compiler.

The computer models simulate by finite difference approximation, the transfer of heat from one volume element of rock to another with time. The

programs compute the changes in element volume due to heating and cooling as well as by melting and crystallization. Uplift and/or subsidence, including the effects of isostatic adjustments are then computed. One set of programs (see appendix 1 for source code) ran the simulations using parameters covering a geologically reasonable range of initial conditions for basin development (see tables 7 and 8). The output of the simulation programs was saved as text files on microcomputer compatible disks. Another program (see appendix 2 for source code) then graphed and displayed the results as uplift or subsidence vs. time and printed the graphed results on a Hewlett-Packard Laserjet 4L printer (see Appendix 3 for the graphical output of the computer simulations).

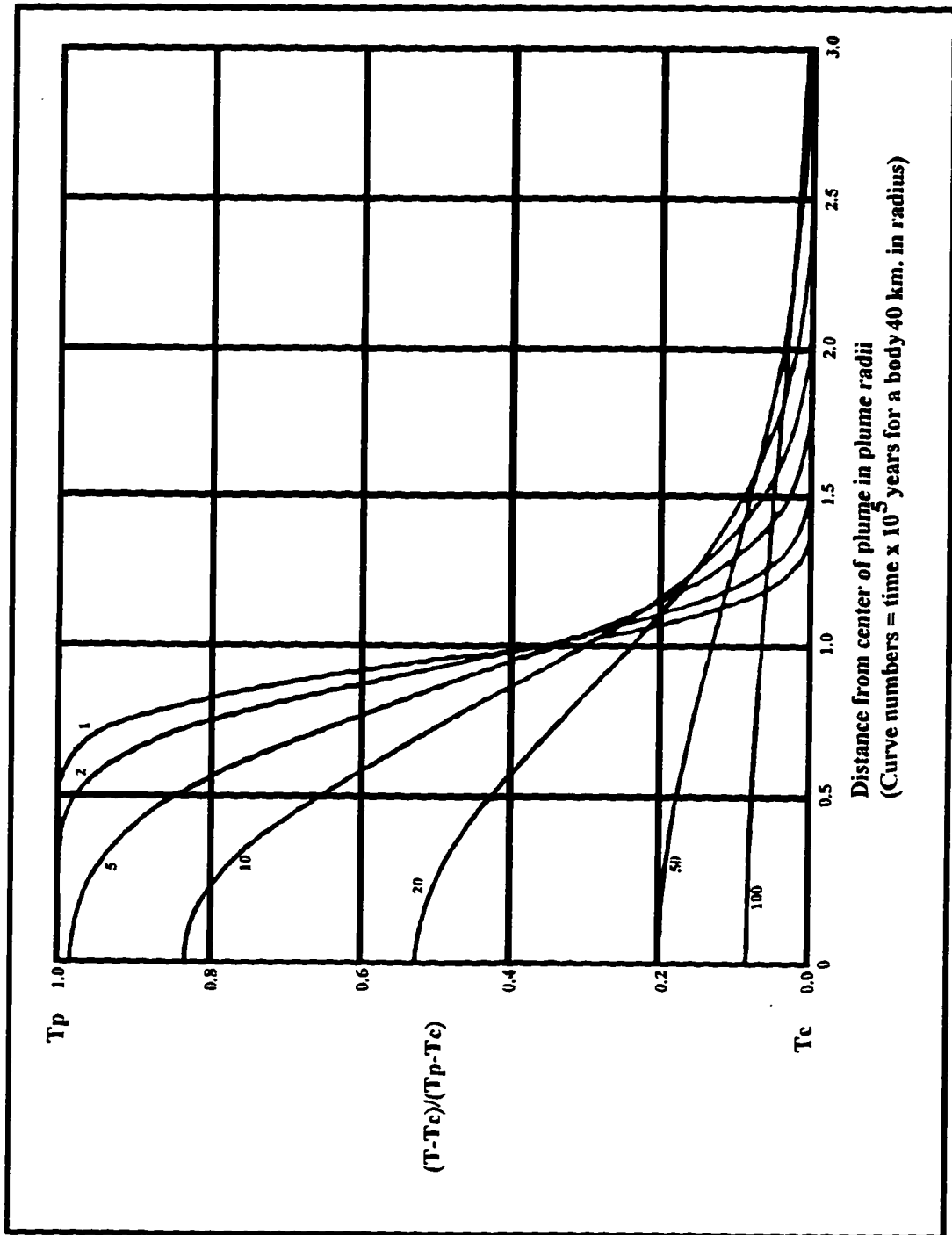
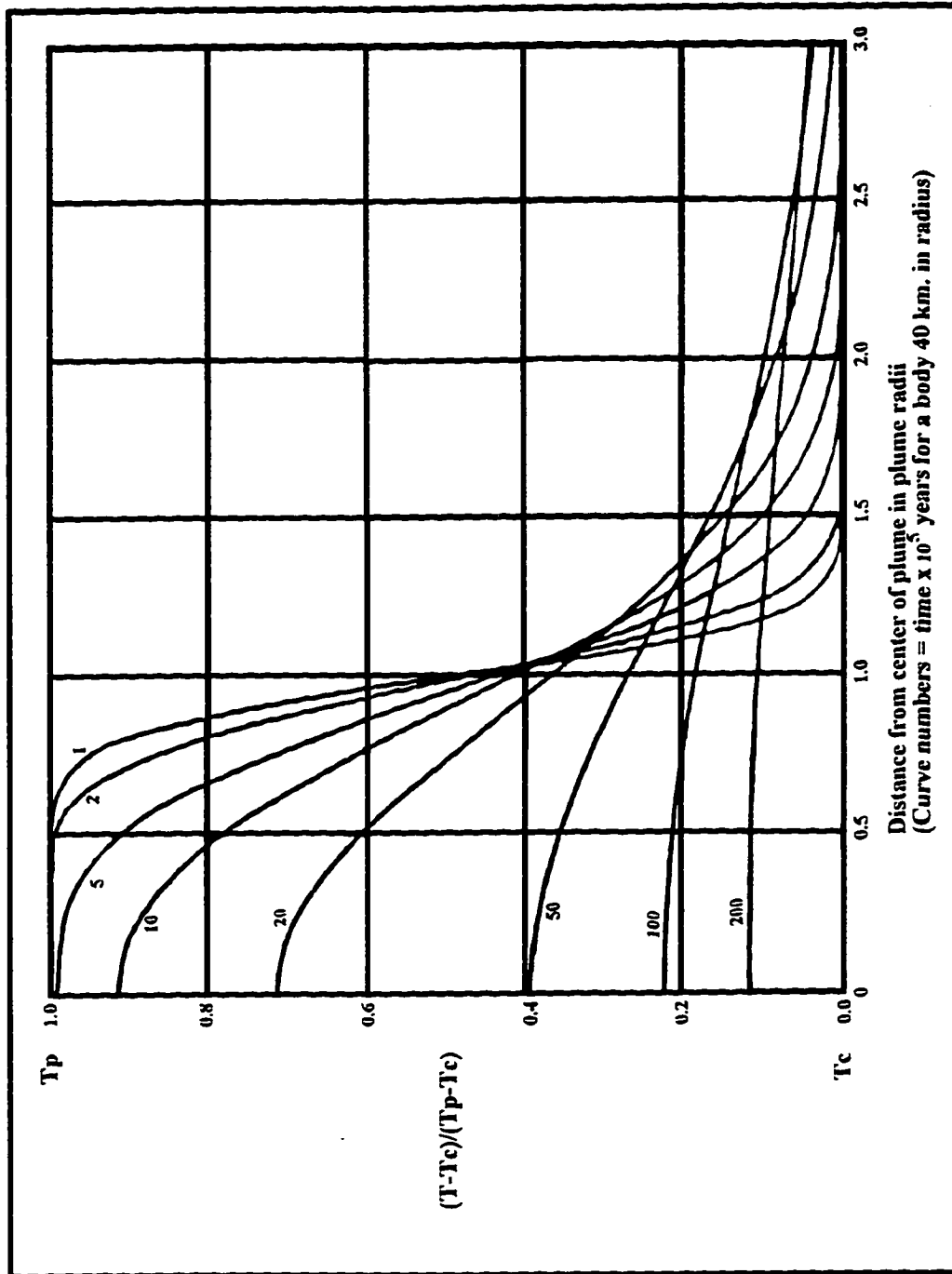


Figure 15 Heating of surrounding rocks by a spherical body (from Carslaw and Jaeger, 1959)



Distance from center of plume in plume radii  
(Curve numbers = time x 10<sup>5</sup> years for a body 40 km. in radius)

Figure 16 Heating of surrounding rocks by a cylindrical body (from Carslaw and Jaeger, 1959)

## **Model Parameters and Assumptions**

**The Airy model of isostatic adjustment may be applied in those cases where the continuity of the lithosphere is interrupted by steep faults and/or fractures so that vertical loads on one block are not significantly transmitted to adjacent blocks (Miall, 1990). In the case of the Cuddapah Basin, there is ample evidence from geophysical (Kaila et al, 1979; Rao et al, 1987) and the Landsat data (see Plate 1) of the presence of such steep faults and fractures. As previously noted, these are located not only at the boundaries of the Cuddapah Basin but also at the boundaries of the sub-basins within the Cuddapah Basin (see Figures 3, 4 and Plate 1). Where such conditions do not occur the transfer of stress to adjacent rocks, and therefore flexure, would be significant, and should be considered when analyzing or simulating intracratonic basin evolution.**

**It is possible that in the case of the Cuddapah Basin vertical movements of the sub-basins could occur independently of the surrounding areas because of the high angle fractures or faults, represented by the lineaments within the Cuddapah Basin and which bound the sub-basin areas (see Figure 5) The transfer of stress, due to vertical movements within the basin, to the adjacent areas, or sub-basins, was limited by the relatively low shear strength of the material at these fracture zones. The model simulations of Cuddapah Basin evolution, developed for this study incorporate this "stress decoupling" as an assumption.**

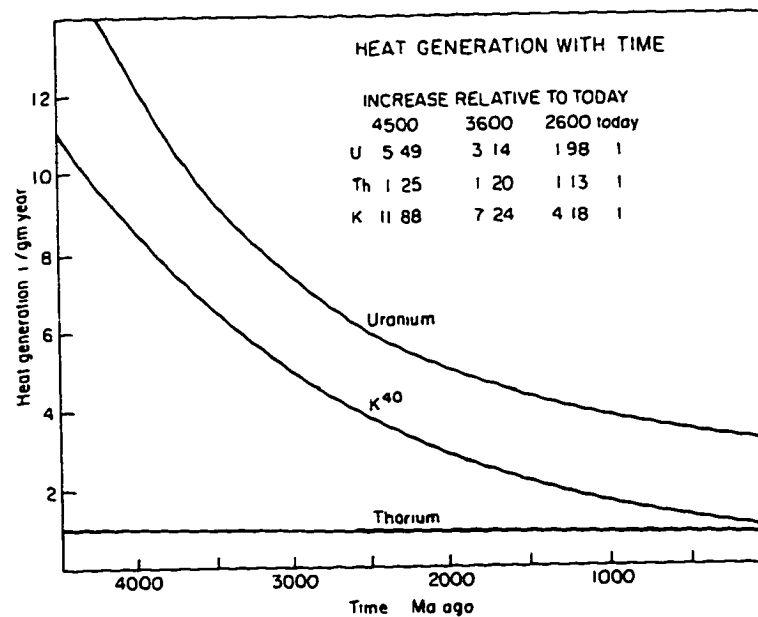
**Bhattacharji (1986) and Bhattacharji and Singh (1984) have shown that, for the Cuddapah Basin mechanisms other than sediment loading must account for at least an additional 2 to 3 km of observed basin depth, over that predicted by an Airy type model. They have hypothesized a thermal "driving load" to account for this additional subsidence of the basin floor. Bhattacharji (1987) has proposed asthenospheric upwellings (i. e. mantle plumes) during the Proterozoic as the source for this thermal energy as well as the magmatic activity evident in the basin.**

**In the Cuddapah Basin there is considerable evidence of mantle-derived intrusions into the crust in the form of high density bodies which have been detected by deep seismic sounding (DSS), magnetic and gravity surveys (Kaila et al, 1987; Tewari and Rao, 1990; Baburao et al, 1987). Geophysical evidence in the form of a gravity high (Qureshy et al, 1968) and DSS profiles (Tewari and Rao, 1987) points to the presence of a high density body beneath the Papaghni sub-basin consistent with an intrusion of mantle material. Tewari and Rao (1990) have shown evidence for the intrusion of mantle derived material under the eastern part of the Cuddapah Basin as well.**

**Salop and Scheinmann (1969) postulate that the thermal environment of the cratonized crust and upper mantle was significantly different during Precambrian time than during Phanerozoic time. This suggests that the evolution of Proterozoic intracratonic basins may have differed significantly from that of younger**

**Phanerozoic examples. Therefore, Proterozoic thermal conditions, rather than those of the modern earth, must be incorporated into any model simulation of Proterozoic basin evolution.**

**The lithospheric geothermal gradient was greater and mantle perturbations and plume activity were more frequent and intense during the Precambrian than during the Phanerozoic (Strong and Stevens, 1974). Figure 17 shows the decrease in radiogenic heating due to three significant radioisotopes with time.**



**Figure 17 Radiogenic heating with time (From Windley, 1977 after Lambert, 1976)**

**Figure 18 shows geothermal gradients inferred for the Archean, the Proterozoic and the Phanerozoic to the present time, as well as a wet peridotite solidus (considered as a hypothetical mantle rock for purposes of this study), a dry peridotite solidus, and an inferred Proterozoic peridotite solidus between these two extremes. As Windley (1977) has pointed out, the peridotite solidus has migrated upward with time due to outgassing, while the geothermal gradient (following Figure 18) has migrated downward due to a decreasing rate of radiogenic heating.**

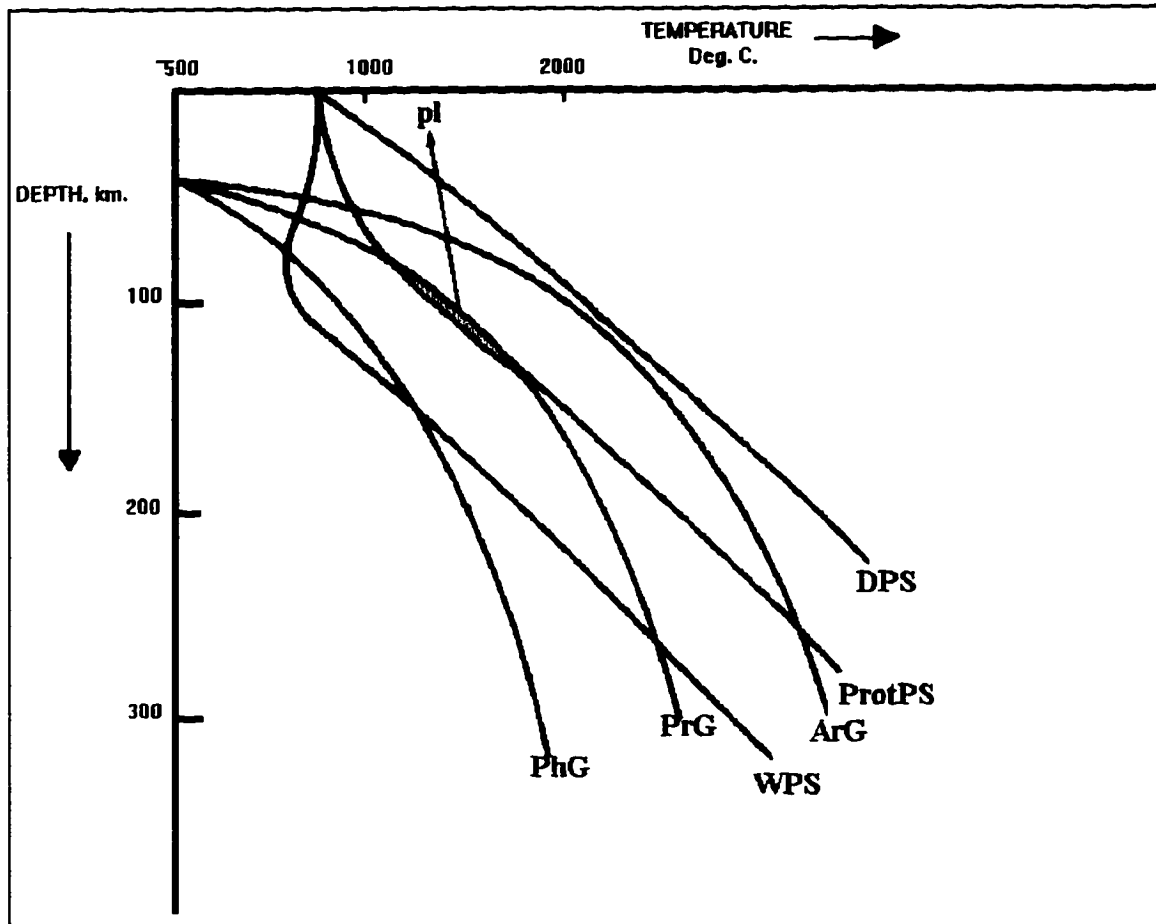
**After Proterozoic time, the peridotite solidus and the geothermal gradient curves no longer intersect and mantle-derived magmatism becomes considerably more restricted and localized (primarily to rift and subduction zones) compared to earlier times (Windley, 1977). Considering this factor, the author suggests that the Phanerozoic intracratonic basins could not have evolved in quite the same manner as have Proterozoic intracratonic basins such as those located on the Indian Peninsular shield.**

**A diapiric plume rising adiabatically from the shaded area of Figure 18 (which represents the hypothetical depth-temperature conditions for the generation of Proterozoic mantle plumes) would be emplaced into the upper lithosphere at a temperature of approximately 1300 °C. This is in substantial agreement with estimates of plume temperature for the Cuddapah Basin, based on geochemical data (Chatterjee et al, in prep., 1995). Therefore, initial plume temperatures ranging**

from 1000 to 1700 °C are used as assumptions in the computer model simulations for this study. This range would include all geologically reasonable conditions.

It is logically obvious that an intrusive body as it develops in nature does not appear suddenly at its final maximum dimensions. Intrusives grow in size (perhaps by multiple injections of magma) from an initial intrusion over a period of time. Considering the model simulation of this process and given the range of typical thermal diffusivities for natural rock (see Table 7) the rate of growth of a plutonic body by assimilation, stoping and/or other processes would exceed the speed at which heat is conducted through the surrounding rock. When this is not the case, the intrusive body will crystallize rather than grow in size. Hence, the net effect of the growth of an intrusive body, may be considered as the cooling of the intrusive body by the assimilation or incorporation, of country rock. Therefore, the model simulations for this study begin with the intruded body at its maximum dimensions. The effects relating to the growth of the magmatic body are accounted for in the assumed initial temperature of the intruded body at its maximum dimensions.

An important factor influencing the ultimate thickness of sediments in a basin is the amount of material removed from the surface during the initial, uplift phase of the basin's evolution. Preliminary work done for this study, as well as the work of others (Haxby, 1976; Sleep, 1971) indicate that there is a rapid, initial uplift phase of thermal basin evolution which is relatively short in duration compared to



**Figure 18** Relationships Between Geothermal Gradients and Peridotite Solidus

**pl**=diapiric plume rising adiabatically; **DPS**=dry peridotite solidus;  
**WPS**=wet peridotite solidus; **ProtPS**=Proterozoic peridotite solidus;  
**Arg**=Archean thermal gradient; **PrG**=Proterozoic thermal gradient;  
**PhG**=Phanerozoic thermal gradient

(Modified from Windley, 1977 after Strong and Stevens, 1974)

the subsequent subsidence phase (see Figure 12). There appears to be a significant problem with invoking erosion, by itself, as the mechanism for the crustal thinning

necessary to provide the initial space for the deposition of basin sediments. The problem is that typical rates of crustal erosion are not sufficiently great to provide the necessary space during the relatively brief period of uplift that would, according to this model, precede the much slower subsidence phase of basin evolution. The author notes, however, that while published estimates for typical rates of surface erosion are on the order of 1 cm in 100 years, (Verhoogen et al, 1970), these estimates are for the unsubmerged portions of the continents as a whole. Rates of erosion are quite variable, depending upon the lithology of the rocks being eroded, paleoclimate and topography, among other things, and can, for the uplifted areas, be significantly greater (op. cit., 1970).

Other processes that have been suggested to account for the crustal thinning necessary for the development of sedimentary basins such as the Cuddapah Basin include gravity tectonics (i. e. "gravity sliding"), viscoelastic extension (i. e. unrecovered viscoelastic strain (Watts et al, 1982), pure shear faulting (McKenzie, 1978), and simple shear (listric) faulting (Wernicke, 1985). The crustal thinning involved in basin evolution is clearly due to some combination of these processes, as well as surface erosion.

The degree of thinning of uplifted basin rocks by these processes is difficult to estimate. However, between the geologically unrealistic extremes of no crustal thinning, and that of erosion plus other crustal thinning processes keeping pace with

uplift, (which would require either extremely slow uplift over an unreasonably long period of time, or a very high rate of erosion and/or other gradational processes), there are geologically reasonable estimates with which to perform the model simulation. For purposes of these model simulations, rates of removal of uplifted basin material by all of the above mentioned processes, ranging from  $10^{-5}$  meters/yr to  $10^{-3}$  meters/yr are assumed.

Computer simulations were accomplished including the thermal and physical properties of the earth materials involved, as listed in table 7 (Bhattacharji, 1974; Carslaw and Jaeger, 1959), and the assumed initial conditions as listed in table 8.

|  | <u>Gabbroic Rock</u> | <u>Granitic Rock</u> | <u>Sedimentary Rock (Avg.)</u> |
|--|----------------------|----------------------|--------------------------------|
| Heat Capacity<br>cal cm <sup>-1</sup> deg <sup>-1</sup>  | 0.30                 | 0.21                 | 0.23                           |
| Thermal Diffusivity<br>cm <sup>2</sup> sec <sup>-1</sup> | 0.008                | 0.011                | 0.008                          |
| Magma Density<br>gm cm <sup>-3</sup>                     | 2.6                  | 2.5                  | —N/A                           |
| Rock Density<br>gm cm <sup>-3</sup>                      | 3.0                  | 2.8                  | 2.4                            |
| Coefficient of<br>Thermal Expansion<br>deg <sup>-1</sup> | $2 \times 10^{-5}$   | $5 \times 10^{-5}$   | —                              |
| Heat of Fusion<br>cal gm <sup>-1</sup>                   | 0.70                 | 0.70                 | 0.70                           |

Table 7  
Thermal and Physical Properties of Materials used for Model Simulations

|  |   |
|--|---|
| <b>Mean depth of basin sea</b>                                   | <b>50 m</b>   |
| <b>Emplacement depth of plume</b>                                | <b>4 to 9 km</b>  |
| <b>Initial plume temperature</b>                                 | <b>1000 to 1700 °C</b>  |
| <b>Rate of removal of uplifted material<br/>(i. e. thinning)</b> | <b><math>10^{-5}</math> to <math>10^{-3}</math> meters/year</b> |

**Table 8**  
Above conditions are assumed for model simulations

The lithology of the basin sediments is in general indicative of a shallow marine to littoral environment of deposition. This is shown by the glauconitic facies in the quartzites of the Cuddapah Supergroup, the presence of cross-bedding in the Gulcheru, Gandikota, Nagari, Bairenkonda, Banganapalle and Panem quartzites, the presence of stromatolites in the carbonate facies of the Vempalle and Tadpatri formations, and reef structures in the dolomitic facies of the Pullampet formation (Nagaraja Rao et al, 1987; Williams et al, 1982).

For these reasons, the mean initial depth of the basin sea in the model simulations was assumed to be 50 meters. This is on the shallow end of a range of reasonable depths in basins.

In order to estimate the magnitude of the error that could be introduced by actual variations in basin water depth from the model assumptions, the author

considered the difference between the maximum thickness of sediment that could accumulate due to isostatic adjustment with a water depth of 50 meters and one of 500 meters, which is on the high end of what is geologically reasonable.

Considering the relationship demonstrated by Jefferys (1962):

$$A = h(\rho_m - \rho_w)(\rho_m - \rho_s)^{-1}$$

and 
$$\Delta A = \Delta h(\rho_m - \rho_w)(\rho_m - \rho_s)^{-1},$$

where  $A =$  depth of sediment (maximum)

$\Delta A =$  difference in sediment depth (maximum)

$\rho_m =$  mantle density

$\rho_w =$  water density

$\rho_s =$  sediment density

$h =$  water depth

$\Delta h =$  difference or discrepancy in water depth

assuming;  $\rho_m = 3.40$

$\rho_w = 1.03$

$\rho_s = 2.40$

then;  $\Delta A =$  (maximum difference in sediment thickness) 1.07 km

Therefore the maximum difference in sediment thickness due to the maximum credible discrepancy in actual water depth with the assumptions of the model, would be on the order of one kilometer. The author considers that, given the clear and

**consistent indications in the basin lithology of relatively shallow water depth for most of the times of deposition (Nagaraja Rao et al, 1987) actual discrepancies would be much smaller than one kilometer. These differences would not significantly affect or change the conclusions of this study.**

**Assumptions for the depth of emplacement (from the surface at the time of emplacement) are taken from geophysical data establishing the depth of dense material below the present basin floor (Tewari and Rao, 1990, 1987; Kaila et al, 1979). A range of values is taken to allow for possible effects of surface erosion during the uplift phase of basin evolution (see Table 8).**

**In the display and print program used for this study the initial depth of emplacement of a hypothetical mantle plume for each simulation is printed at the top of each page of graphed output along with the simulation number (which simply reflects the sequential order in which the simulations were done) and the assumed initial plume temperature. The graphed output shows subsidence of the basin floor in kilometers as predicted by the simulation and plotted against time in millions of years.**

## **Results and Discussion**

**The analysis of the Landsat MSS images indicates that lineaments appear to bound the Papaghni, the Nallamalai, and the Srisailam sub-basins. Deep Seismic Sounding profiles reported by Kaila et al (1979; see Figure 14) show some of these lineaments to represent deep, high angle discontinuities (i. e. fractures or faults) that extend down through the MOHO. This suggests that these discontinuities are surfaces along which the sub-basins of the Cuddapah Basin have moved vertically relative to one another (i. e. they are "stress decoupled" from one another by the discontinuities). The intersection of these discontinuities with the surface produces the lineaments, which appear in the satellite imagery. Figures 3, 4 and Plate 1 indicate that these faults or fractures break up the Archean lithosphere into blocks, some of which underlie the sub-basins of the Cuddapah Basin. It is these blocks that were decoupled from one another with respect to the transfer of stress due to vertical movements during the evolution of the Cuddapah Basin.**

**Simulations 1 through 34, 36, 37, 40 through 43 and 49, whose graphical output is shown in Appendix 3, model the response of the surface of a lithospheric block beneath a sub-basin, to a hypothetical plume of mantle derived material intruded into the crust at depths ranging from 3 to 9 kilometers below the surface. The graphs show the simulated maximum thickness of sediment accumulation, due to subsidence. They are plotted against time.**

The simulations indicate that subsidence, and therefore sediment thickness, ranging from about 11 kilometers to about 17 kilometers could be expected due to the combined effects of thermal expansion and contraction, volume changes due to melting, crystallization, and isostatic adjustment to crustal thinning and sedimentation (see Appendix 3). These results are consistent with the thicknesses of sedimentary rock observed in the basin at present, particularly when one considers that some basin material has been removed by erosion to expose it in its present position. The model should therefore, be expected to show at least the thickness of sedimentary rock observed in the basin minus the depth of the basin sea and probably more to account for that thickness of basin sediments which has been lost due to subsequent erosion.

The thickness of sedimentary rock reported from the Cuddapah Basin ranges from 7.5 kilometers to 12 kilometers (Nagaraja Rao et al, 1987; Bhattacharji, 1981) and is consistent with the results of these model simulations.

The model simulations in this study demonstrate that the subsidence of the basins or sub-basins would approximate the pattern of subsidence predicted by Sleep (1971) and Keen (1979). Rates of subsidence decrease with time in a fashion which appears to be, but is not precisely logarithmic (see simulations 1 through 34, 36 through 43 and 49, in Appendix 3). The expectation of a logarithmic relationship of subsidence with time is based on the assumption of cooling by thermal conduction

**of heat to the surface and the consequent thermal contraction of the cooling rocks. It does not take into account the effects of melting and crystallization in the intruded mantle derived material or in the adjacent country rocks as does the model employed in this study.**

**For the entire range of reasonable geological assumptions used for these simulations, significant uplift, subsidence or basin activity due to a single thermal event (i. e. mantle intrusion) no longer occurs after an interval of between 10 and 20 million years from the time of the event (see Appendix 3, Simulations 1 through 34, 36 through 43, and 49). The larger the intrusive body, the longer the period of time over which tectonic activity due to its thermal effects would occur. The time over which significant vertical basin movement could be sustained appears from these simulations to be roughly proportional to the square of the thickness of the body. (The minimum dimension in the case of non spherical bodies). However, a period of about 30 million years would not be exceeded, even for a body 50 kilometers in diameter.**

**Figure 13 shows the simulated distribution of temperature, at selected times, in rock overlying a tabular intrusive body with an initial temperature of 1000 °C, due to heating by that body. In this case the body is assumed to have been emplaced 4 kilometers below the surface. After about 1.6 million years, the heat lost to the surface becomes greater than the heat transmitted by the body to the**

overlying rock. After that time, cooling of both the overlying crustal rocks and the intruded body would occur. Consequently, thermally induced subsidence would begin at this time as well.

Figures 15 and 16 show the redistribution of heat to surrounding rock from compact spherical and cylindrical bodies respectively. The curve numbers show the expected temperatures at various distances from the intrusive bodies, at selected time intervals. Distances are shown in terms of the radius of the hypothetical intrusive body. The times shown are based on a body 40 kilometers in radius. This value was chosen because it is on the high end of what is geologically credible.

All of these simulations show that significant thermally induced tectonic activity over an intrusion up to 40 kilometers in radius, with assumed initial temperatures of 1000 to 1700 °C, would not persist for more than 30 million years from the time of the intrusion. Smaller intrusive bodies would produce effects lasting for shorter periods of time. Therefore one can conclude that no single episode or event of intrusion could account for the total evolutionary history of activity in the Cuddapah Basin which has lasted for a period estimated to be from 700 million to over a billion years (Bhattacharji, 1987; Rao et al, 1987).

Padmakumari and Dayal (1987), Bhattacharji (1987) and Murthy et al (1991) have reported radioisotopic ages for mafic dikes, sills, and lava flows in and around the Cuddapah Basin (see Tables 3, 4, and 5). In each of these studies the results

show at least three distinct groupings of ages for these rocks indicating three clear periods of igneous activity at the Cuddapah Basin separated by periods of more than 300 million years. They also show igneous activity at much later times, 640 to 520 million years, which Padmakumari and Dyal (1987) theorize may be related to collision tectonics which occurred as the last of the activity in the Cuddapah Basin.

Although the data reported by Padmakumari and Dyal are not statistically significant, the author, for purposes of illustration, has taken the liberty of averaging the ages within each group and computing the time intervals between them. The results are shown below:

| <u>Age of group</u> | <u>Time interval</u> |
|---------------------|----------------------|
| 644 my.             | .....454 my.         |
| 1098 my.            | .....364 my.         |
| 1462 my.            | .....312 my.         |
| 1774 my.            |                      |

The groupings of the ages of the magmatics associated with the Cuddapah Basin shown above, indicate that material, derived from the mantle, affected different parts of the basin at different times of its evolution (see Figure 19).

Tewari and Rao (1987 and 1990) have reported evidence for the presence of mantle derived material under the eastern part of the Cuddapah Basin. Their velocity analysis of first arrival refraction data has yielded indications of a high velocity zone at depths varying from 3 to 15 km. They concluded that the crust-mantle boundary in this area is highly disturbed due to mantle intrusion. Kaila et al (1979) have reported similar findings under the western side beneath the Papaghni sub-basin of the Cuddapah Basin based upon the interpretation of deep seismic sounding data and gravity studies.

Murthy et al (1991) observed a gravity high (about +60 milligals), surrounded by a broader gravity low area (about -23 milligals) in the area of the Cuddapah Basin. These data are consistent with high density material having been injected into the crust, the subsequent subsidence of the Archaean crust and the deposition of lower density sediments onto the subsided surface.

Mishra et al (1987) integrated gravity and paleomagnetic data from the Cuddapah Basin. They inferred the presence of a large mafic body under the basin at depths of up to 7.5 Km. They note that the orientation of paleomagnetism in the dikes and sill of the lower Cuddapah Basin units suggests that they might be

**synchronous with, and derived from, the mafic body below.**

**Based upon the results of this study and the above evidence it can be concluded that there have been at least three events of thermal reactivation under the Cuddapah Basin. Four, if one includes magmatism related to the Pan African Orogeny. The evidence also supports the suggestion by Bhattacharji (1984 and 1986) that pre-existing zones of lithospheric weakness have influenced the location of the surface effects of mantle plumes and the evolution of Proterozoic intracratonic basins such as the Cuddapah Basin.**

**Expressed simply, mantle plumes appear to have most significantly affected those areas of the lithosphere in the area of the Cuddapah Basin which offered the least resistance to vertical movements (i. e. those bounded by deep lithospheric fractures or faults). The most frequent occurrence of such lineament-bounded blocks would be in the area of the intersection of major lineaments (see Figure 1). Erosion of the upper surface of these areas during periods of upliftment has produced the unconformities observed within the basin.**

**The subsequent decrease in the volume of the underlying intruded material due to contraction by cooling, crystallization and the transfer by magmatism, of material from under the sub-basin to areas outside of the sub-basin has caused subsidence. This provided the space necessary for the deposition of the basin sediments. The effect on basin subsidence of the transfer of magma to areas outside**

of the basin is difficult to quantify and has not been addressed with the computer simulations done for this study. This effect would however, add to the subsidence due to the other factors considered.

As a sub-basin subsides, sediment derived from the surrounding area loads the basin floor and causes continued subsidence until isostatic equilibrium is re-established. Consequent upon the uplift of one sub-basin area, sediment derived from the uplifted area is deposited in the adjacent sub-basin. The removal of eroded surface material, increases the magnitude of the uplift of the raised area, due to isostatic adjustment; while loading due to the deposition of this material is causing subsidence of the adjacent sub-basin. Thus, the sub-basins within the Cuddapah Basin can be considered as yoked basins (see Figure 19, stage 5).

This yoking mechanism, which is consistent with the Landsat data, the radioisotopic ages derived from igneous rocks associated with the basin, basin stratigraphy, and the model simulations, explains the depth of the sediment in the Cuddapah Basin, the vertical movements of the sub-basins relative to one another, and the evident timing of the movements of the sub-basins. This is also consistent with the long history of basin activity.

Three distinct episodes of igneous activity occurring at time intervals of more than 300 million years have placed mantle-derived material under the area of the Cuddapah Basin. Each time this igneous activity affected more of and different

parts of the basin. Because the sub-basins were likely to be "stress decoupled" from each other by deep lithospheric fractures they were able to move vertically with respect to one another and behave as yoked basins. Emplacement of mantle plumes first affected the Papaghni, and then the Nallamalai and Srisailam portions of the Cuddapah Basin (see Figure 19).

The Kurnool and Palnad sub-basins are the youngest parts of the Cuddapah Basin and are superposed on the older units in the basin (see Figures 4, 7a, 7b, and 7c). The author suggests that these younger sub-basins originated with the tensional component of the stress field during the Nallamalai folding. The hypothesis that the area of the Srisailam plateau was decoupled with respect to stress from the area to the southeast, (i. e. the Nallamalai), is supported by the observation that the intense folding in the Nallamalai does not extend into the area of the Srisailam plateau (Bhattacharji, 1981) (see Figures 4, 7a and 7b).

The area west of the Nallamalai sub-basin was not subject to the intense deformation experienced by the Nallamalai sediments even though some of these sediments were in place when the Nallamalai was folded (Nagaraja Rao, 1987). The area west of the Nallamalai was shielded from the horizontal compressional stress to the east by a reorientation of the stress field at the faulted boundary between the Nallamalai and the units to the west. This would produce a stress field in which the direction of maximum compressive stress ( $\sigma_1$ ) is near vertical, and the minimum

**compressive stress ( $\sigma_3$ ) is oriented northeast - southwest. This could initiate the horst - half graben structure shown in Figure 7c (see stress ellipsoid in Stage 8). Isostatic adjustment to depositional loading would result in further subsidence in the areas of the Kurnool and Palnad sub-basins producing the structures as described below.**

**The contacts between area C in Figure 3, and C1 and C2 are tectonic as has been mentioned. The contacts on the other sides of these two sub-basins are stratigraphic unconformities (Nagaraja Rao et al, 1987) (see Stage 9, in Figure 19).**

Figure 19

**A Summary of the  
Evolution of the Cuddapah Basin**

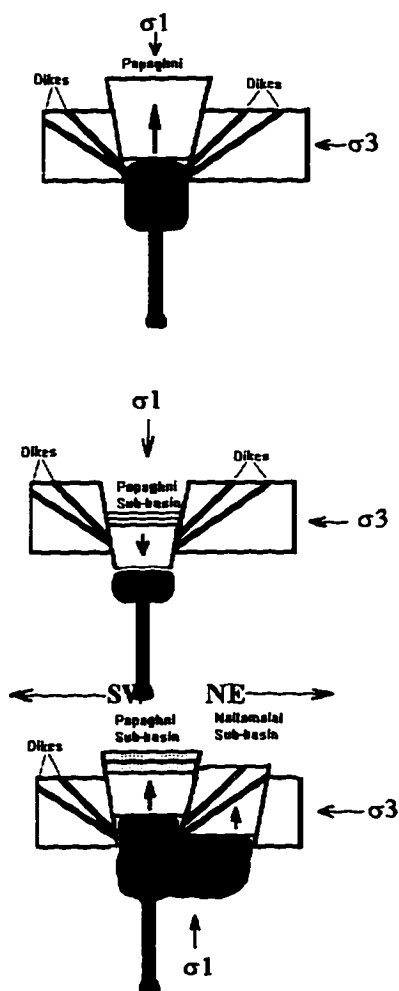
(The diagrams shown in this discussion are schematic representations and are not drawn to scale;  $\sigma_1$ ,  $\sigma_2$  and  $\sigma_3$  represent compressive stress;  $\sigma_1 > \sigma_2 > \sigma_3$ ).

**Stage 1: Major lineaments are created in the cratonized Archean lithosphere representing deep fractures and/or faults,**

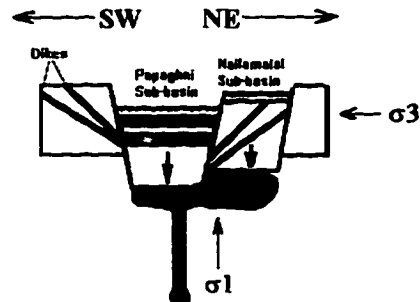
**Stage 2: The area underlying the Papaghni sub-basin, bounded by pre-existing lithospheric fractures (lineaments), is uplifted due to intrusion of mantle derived material. Lag deposit is produced on the eroded surface of the uplifted block. Synchronous magmatic activity commences in the surrounding area,**

**Stage 3: Papaghni subsides with deposition of Gulcheru and Vempalle formations. Granitic Dharwar rocks in source area result in arkosic deposition in Gulcheru over basal lag deposit,**

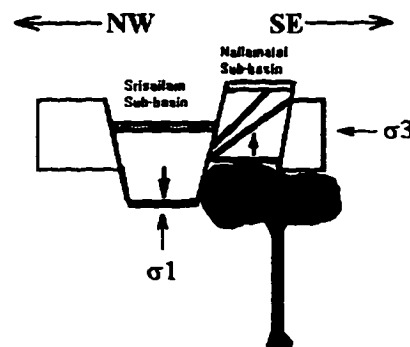
**Stage 4: More intrusive activity, now extending under Nallamalai sub-basin. Papaghni and Nallamalai uplifted. Nallamalai receives sediments derived from Papaghni sub-basin,**



**Stage 5: Nallamalai and Papaghni subside, deposition of Pulivendla, Tadpatri and Gandikota formations in The Papaghni sub-basin area. Deposition of Nagari, Bairenkonda, Cumbum and Pullampet formations in the area of the Nallamalai sub-basin,**

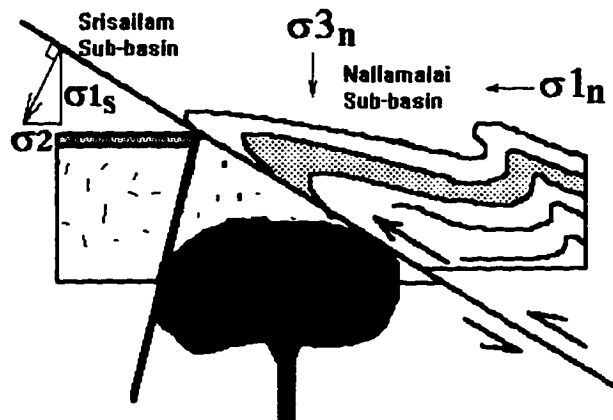


**Stage 6: Third intrusive period, Papaghni and Nallamalai uplifted, Srisailam area receives sediments,**

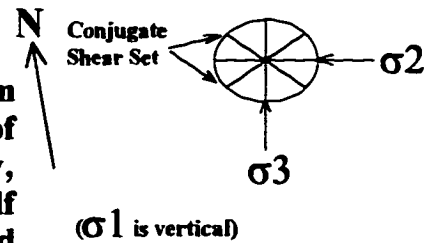


**Stage 7: All sub-basins subside with deposition, cooling and crystallization of magma,**

**Stage 8: Nallamalai folded by collision tectonics. Stress is dissipated by lithospheric discontinuities so that the western part of the Cuddapah Basin remains relatively undeformed. West of the thrust fault separating the Nallamalai and Srisailam areas, the vertical component of compressional stress becomes greater than the horizontal component (the resolution of forces is based on the principle of the wedge),**

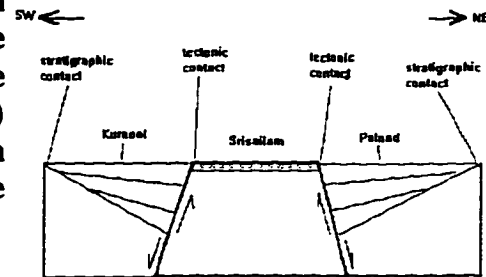


**Stage 8 (continued);** In the northern part of the basin, the tensional component of the stress field west of the thrust boundary, forms the Srisailam horst and the half grabens into which the Kurnool and Palnad sediments are subsequently deposited,



**Stress ellipsoid for area west of thrust fault separating Srisailam Plateau and Nallamalai Fold Belt, showing directions of maximum and minimum compressional stress components.**

**Stage 9:** The Palnad and Kurnool areas subside with depositional loading in the half grabens northeast and southwest of the Srisailam Plateau, creating a tectonic (fault) contact with the Srisailam block and a transgressive stratigraphic contact with the older Cuddapah units,



**Stage 10:** Post Kurnool collision tectonics create the eastern border fault, thrusting Archean rocks of the Dharwar over the younger Proterozoic rocks in the Cuddapah Basin (see Figure 4),

**Stage 11:** Subsequent wrench faulting reactivates some lineaments oriented in an east-northeast direction, offsetting older features in a left-lateral (sinistral) sense (see Figure 4),

**Stage 12:** Erosion of the basin through Phanerozoic time.

## Conclusions

**The conclusions drawn from this study are summarized as follows:**

- (i) The Cuddapah Basin was predisposed to its long and complex history by its location at the intersection of lineaments representing zones of deep seated lithospheric weakness.**
- (ii) Model simulations show that the thermo-mechanical effects of mantle intrusions of the depth and scale indicated by the analysis of field and geophysical data from the Cuddapah Basin are sufficient to produce the subsidence necessary for the deposition of the basin sediments.**
- (iii) At least three separate thermal events, separated in time by periods of over 300 million years, were involved in the evolution of the Cuddapah Basin. No single, geologically credible event could account for the evident long history of activity in the basin.**
- (iv) The intense folding in the Nallamalai sub-basin does not continue west of the thrust faults separating the Nallamalai from the Srisailam and the older sub-basins**

to the west. This is most likely due to the reorientation of the stress field at the fault boundary separating these sub-basins (see Figure 19, Stage 8). This reorientation also produced the stress field necessary for the block type faulting associated with the deposition of the Kurnool and Palnad sediments (see Figure 19, Stage 9).

- (v) Faults associated with the Cuddapah Basin were reactivated in post Cuddapah, and again in post Kurnool times.
- (vi) It can be concluded that because of the significant changes, as outlined in this study, in the thermal and chemical environment of the crust and upper mantle from Proterozoic time to the Phanerozoic it is unlikely that Phanerozoic intracratonic basins could have evolved in a manner similar to Proterozoic basins such as the Cuddapah Basin of South India.

## **Limitations and Indications for Future Work**

**Limitations of this study include the following:**

- (i) The exact depth of emplacement of mantle derived material is not known because of some erosion of the original surface subsequent to the time of emplacement. However, the depth of the dense bodies beneath the present surface of the eroded basin floor is known. The model simulation was done with a range of assumed depths based on this information.**
- (ii) The depth of the basin sea during the evolution of the basin is not known precisely. However, as discussed in the section on model parameters and assumptions, there are lithological indications of a shallow basin sea throughout much of the basin's history, and small errors in the assumed depth of the basin sea would not make a significant difference in the results of the model simulation (see section on model parameters and assumptions).**
- (iii) Because of the erosion of sedimentary basin deposits, during and subsequent to the evolution of the Cuddapah**

**Basin, the presently observed thickness of sedimentary deposits does not represent the total subsidence of the basin floor. However it does represent the minimum amount of subsidence that any hypothetical mechanism or mechanisms for basin evolution should account for.**

- (iv) The volume of mantle derived magma transferred to the surface, in and out of the area of the basin, is not known from the information presently available. This could significantly affect basin subsidence and is not addressed in model simulations done for this study. To the degree that material is transferred by magmatic activity from under the floor of the basin to the surface, the effect would be to add to the subsidence predicted by the model simulation. Therefore, the conclusion that thermal effects are sufficient to account for the depth of the basin is not invalidated by this uncertainty.**
- (v) The simulations done for this study show subsidence rates that would be expected to produce deeper water in the basin than is evident from the lithology of the Cuddapah Basin rocks. The simulations account for**

isostatic adjustment to erosion and sedimentation as well as thermal effects. However isostatic adjustment involves the displacement of viscous material in the upper mantle. A visco-elastic model might show that this would delay the isostatic adjustment to sediment loading so that it is extended significantly beyond the time integration interval. However, Proterozoic mantle viscosities are difficult to estimate. Because the model simulations used in this study do not account for this effect of mantle viscosity they may indicate unrealistically high rates of subsidence. This would affect only the rate of subsidence and not the total amount of subsidence or the ultimate depth of the basin produced.

**Indications for further study include:**

**Computer models that include a consideration of effect of the viscosity of a Proterozoic upper mantle on basin subsidence. This would provide a more realistic indication of the rate of subsidence of Proterozoic intracratonic basins.**

**Studies of other Proterozoic, intracratonic basins on the Indian Shield and**

**elsewhere, to determine if the evolution of these other basins was similar to that of the Cuddapah Basin. This would help to confirm or deny the hypothesis that the thermal conditions for such basin development were unique to the Proterozoic Era.**

**Detailed mapping of lineaments in the Archean Shield of India, using "state of the art" remote sensing and geophysical techniques would aid in testing the hypothesis that the Proterozoic, intracratonic basins tended to develop at the intersections of these lineaments.**

## Appendix 1

**Finite Difference Approximation, Uplift/Subsidence Program  
Source code**

```

SHELL "graphics laserjetii" 'prepare system to print output
DIM T(-1000 TO 1000) 'set array sizes
DIM OT(-1000 TO 1000)
DIM Sb(-300 TO 1000)
DIM Sb$(-300 TO 1000)

CLS
PRINT : PRINT "   Explicit Finite Difference Approximation for Heat
Conduction in
Rock"
PRINT : PRINT : PRINT "                               by Stanley Schleifer, 1994"
PRINT : PRINT : PRINT

START:

READ sim$ 'get simulation number

READ GB 'thermal gradient for Archaean basement rocks

GBB = GB / 10 ' express gradient per 100 m interval

READ GP 'thermal gradient for plume

GPP = GP / 10 ' express gradient per 100 m interval

READ TP 'plume temperature

READ SEXP 'coefficient of thermal expansion for basin sediments

READ BEXP 'coefficient of thermal expansion for Archaean basement rocks

READ PEXP 'coefficient of thermal expansion for plume

READ BDIF 'thermal diffusivity for basement rocks

READ PDIF 'thermal diffusivity for plume

```

**READ SDIF 'thermal diffusivity for basin sediments**

**READ dp 'initial depth to top of plume**

**READ ER 'surface erosion in meters per year**

**ER = 1.6 \* ER 'erosion in 100 m units per 160 yrs**

**READ WD 'depth of basin sea**

**TM = 0**

**OL = 500**

**L = 500 'set vertical distance from surface to depth of compensation**

**BF = BDIF \* 50 'diffusivity of basement rocks\*dt/dl^2**

**PF = PDIF \* 50 'diffusivity of plume\*dt/dl^2**

**SF = SDIF \* 50 'diffusivity of basin sediments\*dt/dl^2**

**dpp = dp 'keep plume depth in km for printing**

**dp = dp \* 10 'express dp in 100 meter increments**

**WD = WD / 100 'express WD in 100 meter increments**

**su = WD 'initialize basement surface**

**ss = WD 'initialize sediment surface**

**FOR x = -1000 TO su - 1**

**T(x) = 20**

**NEXT x 'set surface temperature**

**FOR x = su TO dp - 1**

**T(x) = T(x - 1) + GBB**

**OT(x) = T(x)**

**NEXT x 'set initial basement temperatures according to thermal**

**gradient**

**T(dp) = TP 'set initial top of plume temperature**

**FOR x = dp + 1 TO 999**

**T(x) = T(x - 1) + GPP**

**OT(x) = T(x)**

**NEXT x 'set initial internal plume temperatures**

```

DO
  T(ss) = 20 ' keep surface temperature

  FOR i = ss + 1 TO su
    DT = SF * (T(i - 1) - 2 * T(i) + T(i + 1)) 'finite difference routine
    T(i) = T(i) + DT
    DL = DL + DT * SEXP ' expand/contract rock in volume element
  NEXT i

  FOR i = su + 1 TO dp - 1
    DT = BF * (T(i - 1) - 2 * T(i) + T(i + 1)) 'finite difference routine
    T(i) = T(i) + DT
    IF OT(i) <= 700 THEN IF T(i) > 700 THEN DL = DL + .15 ELSE
DL = DL
  + DT * BEXP
    IF OT(i) > 700 THEN IF T(i) <= 700 THEN DL = DL - .15 ELSE
DL = DL
  + DT * BEXP
    'melt or crystallize with appropriate volume change or expand and
contract
    OT(i) = T(i)
  NEXT i

  FOR i = dp TO dp + 500
    DT = PF * (T(i - 1) - 2 * T(i) + T(i + 1)) 'finite difference routine
    T(i) = T(i) + DT
    IF OT(i) <= 1250 THEN IF T(i) > 1250 THEN DL = DL + .15: dp
= dp - .15
    ELSE DL = DL + DT * PEXP: dp = dp - DT * PEXP
    IF OT(i) > 1250 THEN IF T(i) <= 1250 THEN DL = DL - .15: dp
= dp + .15
    ELSE DL = DL + DT * PEXP: dp = dp - DT * PEXP
    'melt or crystallize with appropriate volume change or expand/contract
rock in
  volume element
    OT(i) = T(i)
  NEXT i

```

$su = su - DL$  uplift or subside basin floor

```

      IF su > 1 THEN su = su + .12 * DL: dp = dp + .12 * DL: ss = su
- WD: IF ss
      > WD THEN ss = WD
      IF su < 1 THEN su = su + .88 * ER: dp = dp - .88 * ER: ss = ss +
      .88 * ER

```

'erode or deposit into basin + isostatic adjustment

$DL = 0$

```

n = n + 1'count iterations
IF n = 100 THEN n = 0: m = m + 1: Sb(m) = CINT(su): Sb$(m) =
STR$(Sb(m))

```

'round su to nearest integral value and convert to string

```

LOCATE 12, 1
PRINT m, sim$

```

```

IF m >= 900 THEN OPEN "O", #1, sim$: PRINT #1, sim$: PRINT #1, TP:
PRINT
#1, dpp: FOR m = 1 TO 900: PRINT #1, Sb$(m): NEXT m: CLOSE #1: m
= 0:
GOTO START

```

LOOP WHILE INKEY\$ = ""

```

DATA sim26, 20, 1, 1700, .0004, .0005, .0006, .01, .01, .005, 8, 1, 50
DATA sim29, 20, 1, 1500, .0004, .0005, .0006, .01, .01, .005, 9, 1, 50
DATA sim30, 20, 1, 1600, .0004, .0005, .0006, .01, .01, .005, 9, 1, 50

```

**DATA sim31, 20, 1, 1700, .0004, .0005, .0006, .01, .01, .005, 9, 1, 50**

**(Note: typical dataset shown)**

## Appendix 2

**Display Program****Source Code**

```
DIM Sim$(50)  
DIM Sb$(600)  
DIM su(600)  
  
SHELL "graphics laserjetii" 'prepare system to print output  
  
START:  
CLS  
INPUT "Simulation file to display"; Sim$  
  
IF Sim$ = "end" THEN END  
  
OPEN "I", #1, Sim$  
INPUT #1, Sim$  
INPUT #1, TP  
INPUT #1, dpp  
FOR m = 1 TO 590  
INPUT #1, Sb$(m)  
NEXT m  
CLOSE #1  
FOR m = 1 TO 590  
su(m) = VAL(Sb$(m))  
NEXT m  
  
SCREEN 12  
FOR x = 50 TO 620 STEP 38  
LINE (x, 30)-(x, 390)  
NEXT x  
  
FOR x = 30 TO 390 STEP 20  
LINE (50, x)-(620, x)  
NEXT x 'draw grid for output graph
```

```

PSET (50, 30), 12 'draw initial point for graph

LOCATE 1, 1: PRINT " "; Sim$; " depth to plume ="; dpp; "km ";
" plume
temp. = "; TP; " deg. C. "
LOCATE 5, 1: PRINT "S";
LOCATE 6, 1: PRINT "u";
LOCATE 7, 1: PRINT "b";
LOCATE 8, 1: PRINT "s";
LOCATE 9, 1: PRINT "i";
LOCATE 10, 1: PRINT "d";
LOCATE 11, 1: PRINT "e";
LOCATE 12, 1: PRINT "n";
LOCATE 13, 1: PRINT "c";
LOCATE 14, 1: PRINT "e";
LOCATE 16, 1: PRINT "K";
LOCATE 17, 1: PRINT "m";
LOCATE 2, 6: PRINT "0";
LOCATE 15, 5: PRINT "10";
LOCATE 28, 28: PRINT "time in millions of years"
LOCATE 26, 7: PRINT "0";
LOCATE 26, 21: PRINT "3";
LOCATE 26, 35: PRINT "6";
LOCATE 26, 50: PRINT "9";
LOCATE 26, 63: PRINT "12";
LOCATE 26, 77: PRINT "15";

FOR m = 1 TO 590
  LINE -(50 + .6333333 * m, 30 + 2 * su(m)), 12
  'graph uplift/subsidence curve for basin floor

NEXT m

DO

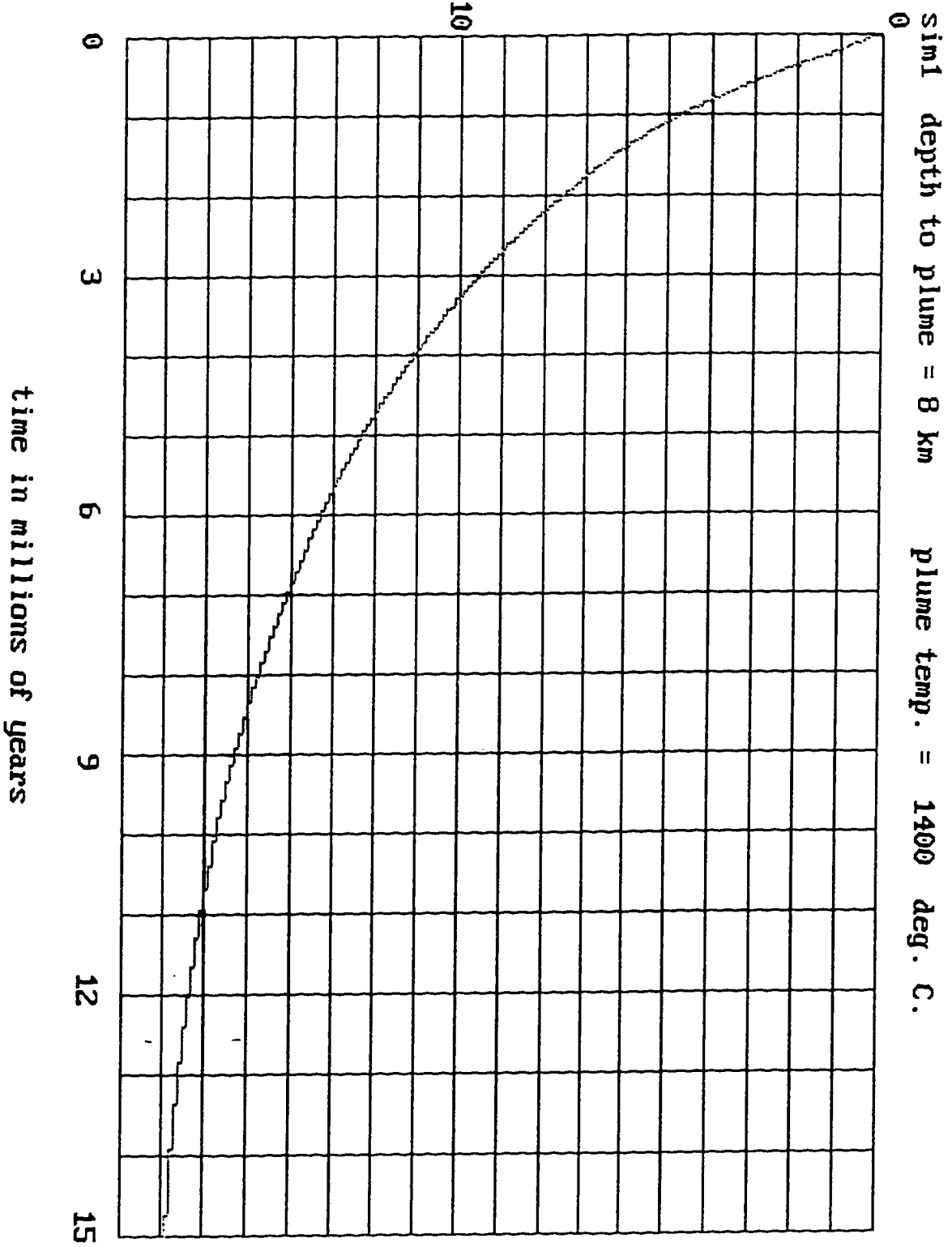
LOOP WHILE INKEY$ = ""

GOTO START

```

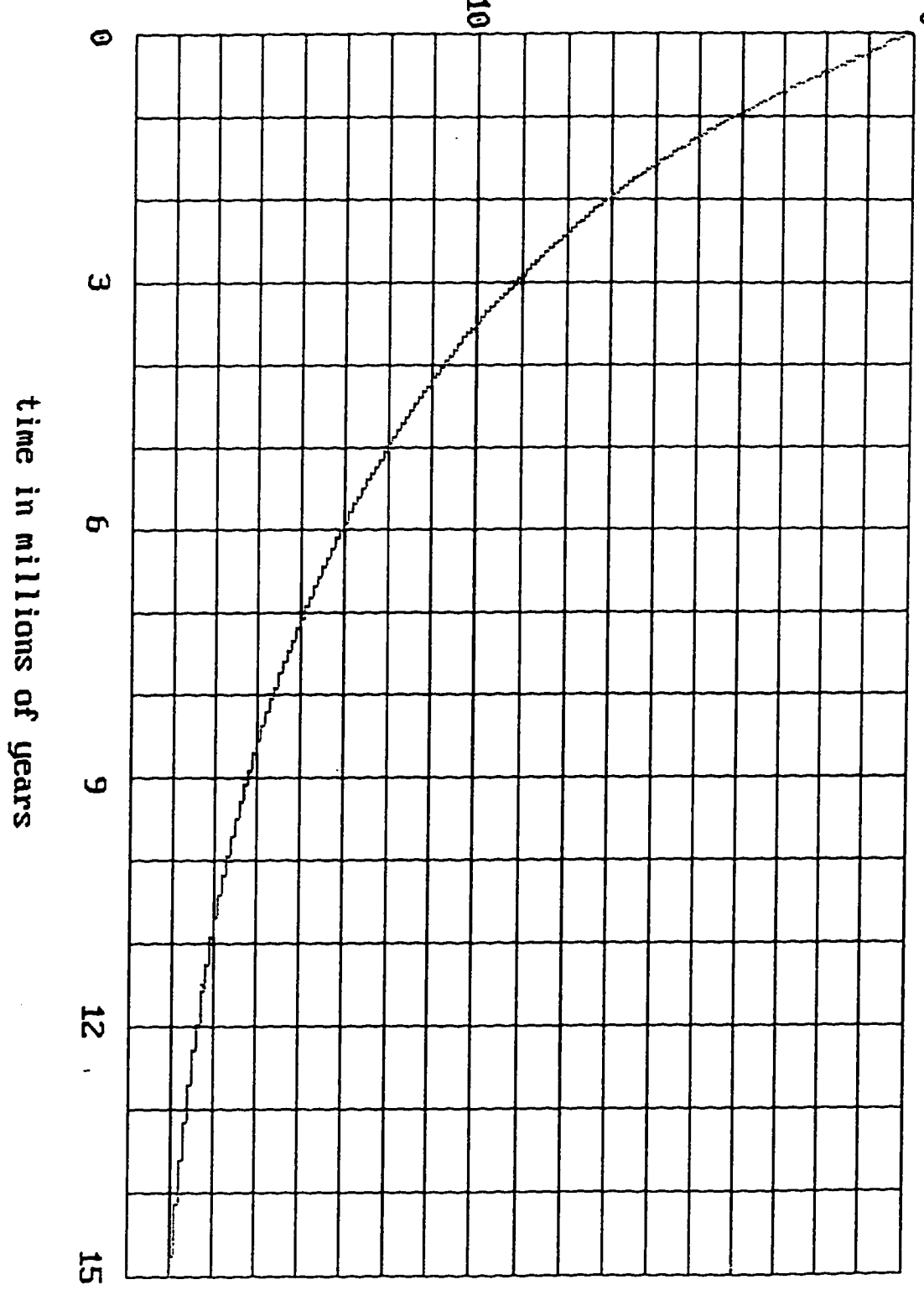
## Appendix 3

S u b s i d e n c e   K m

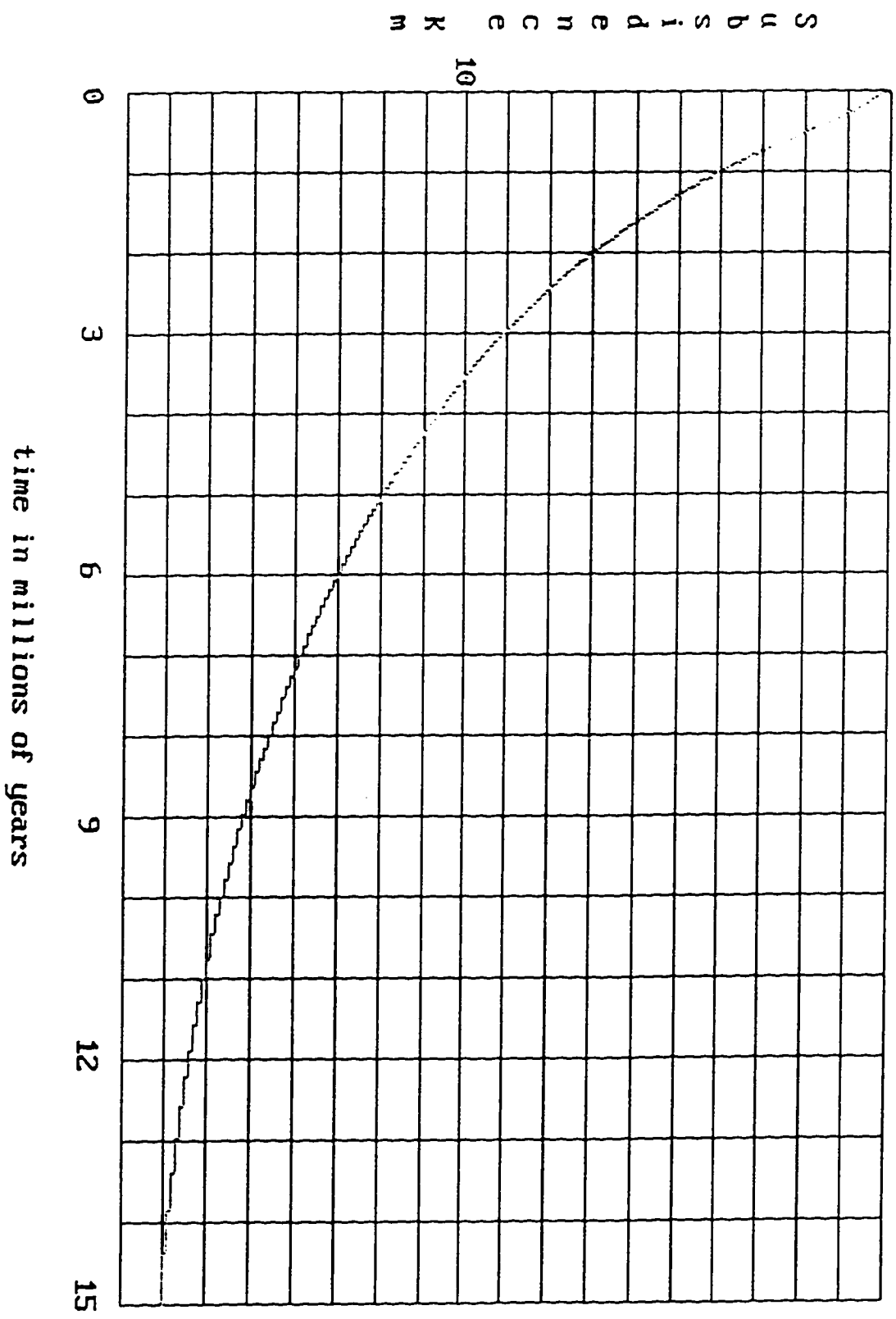


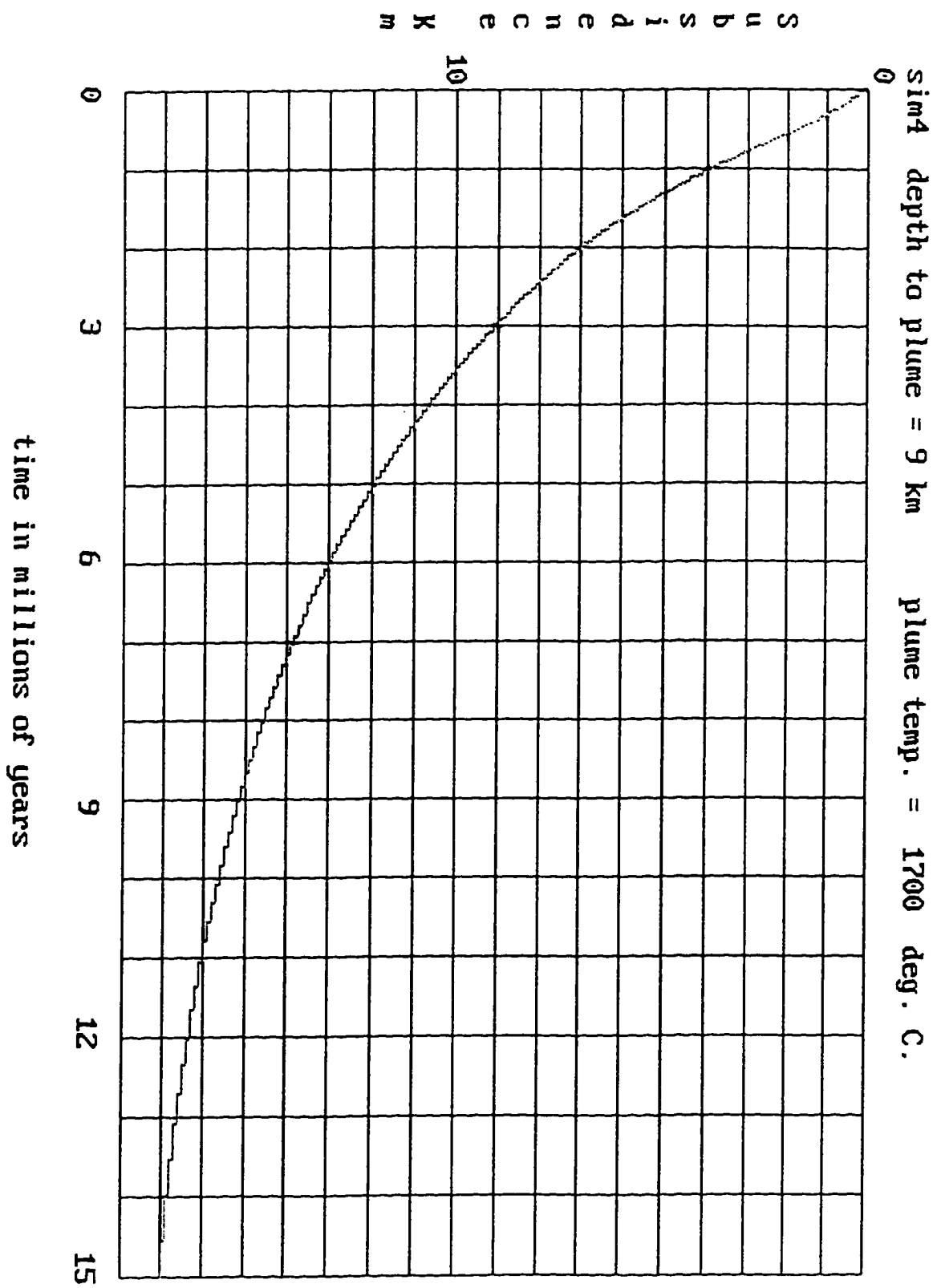
Subsidence Km

sim2 depth to plume = 9 km      plume temp. = 1500 deg. C.

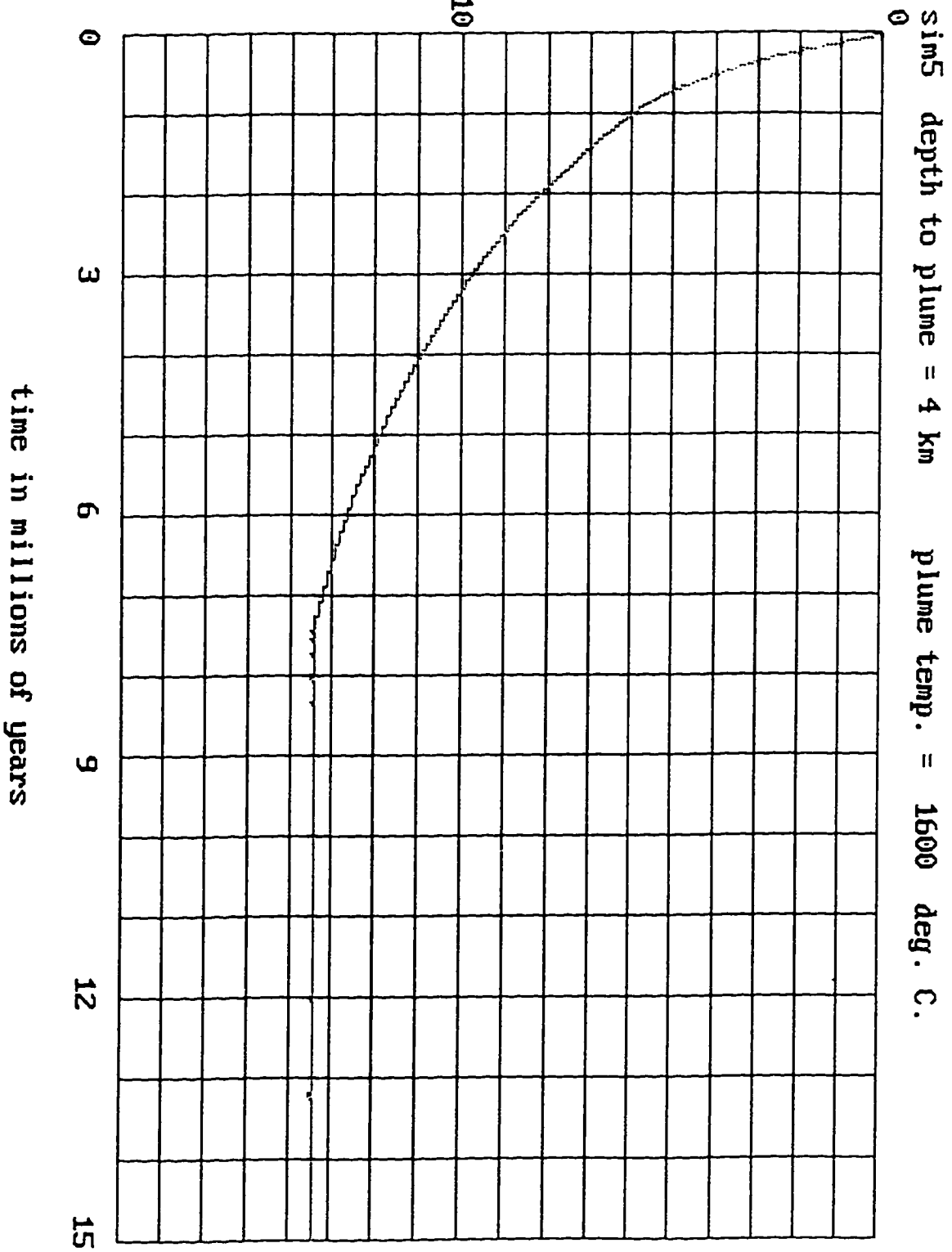


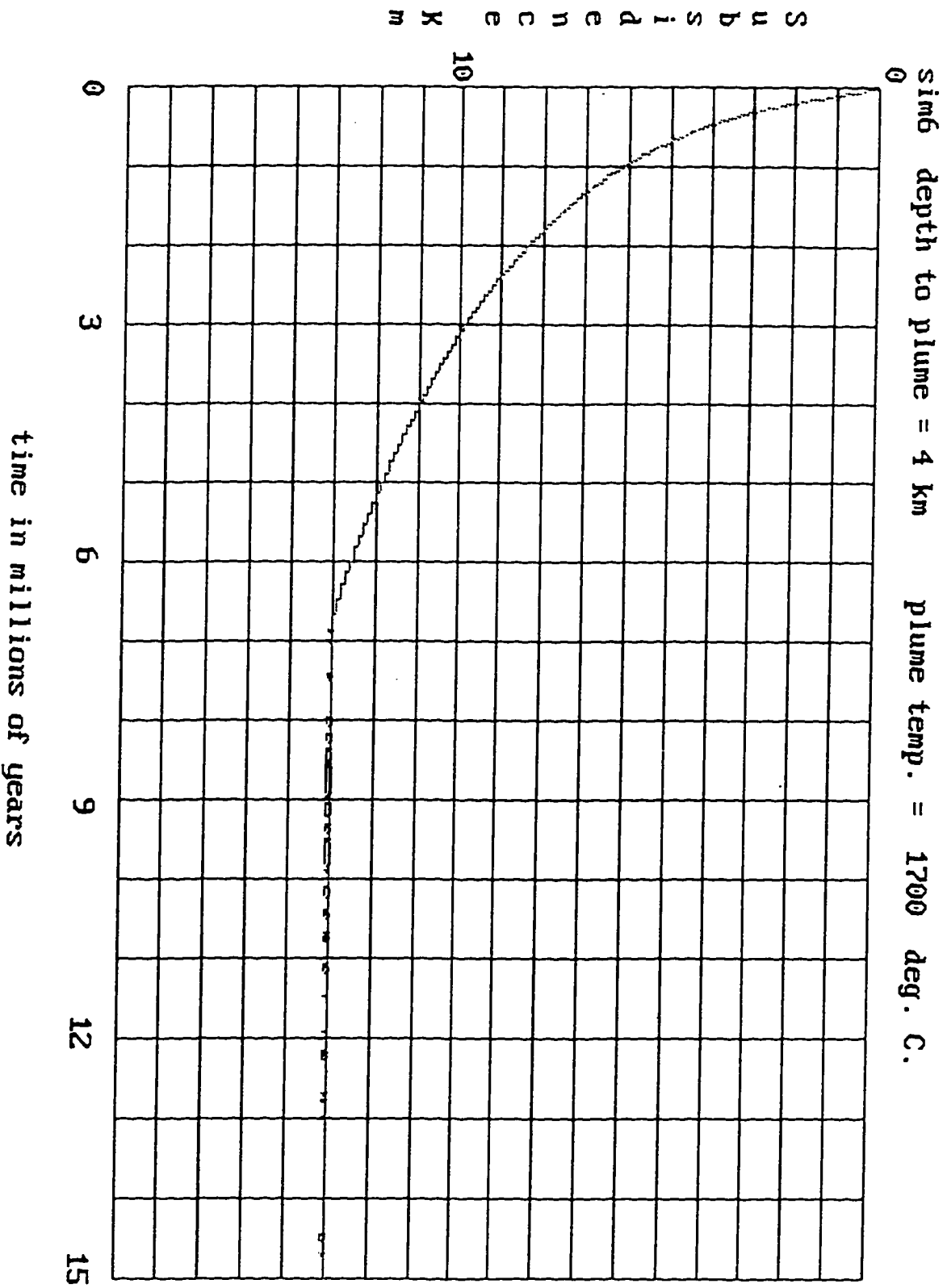
sim3 depth to plume = 9 km plume temp. = 1600 deg. C.

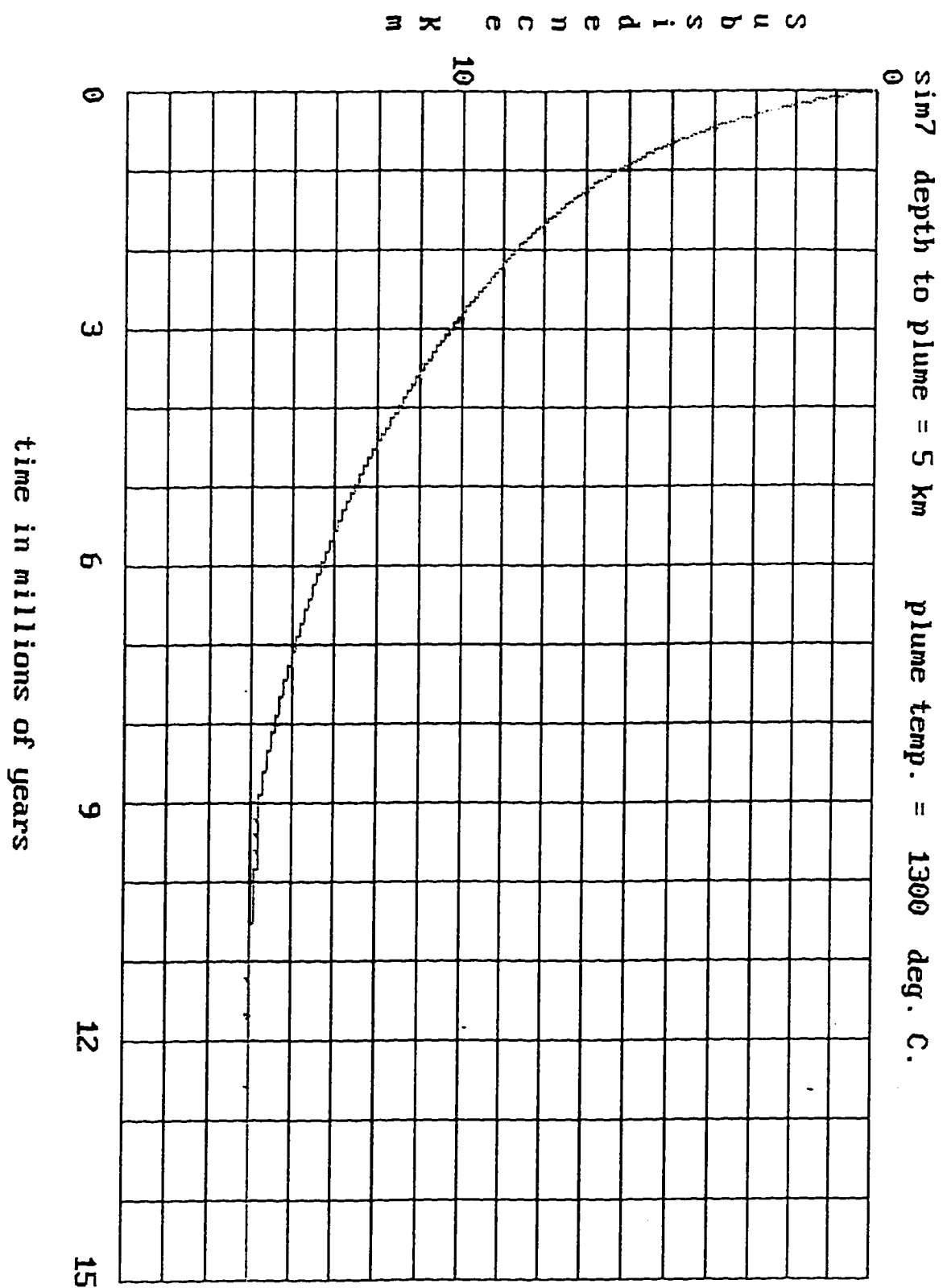


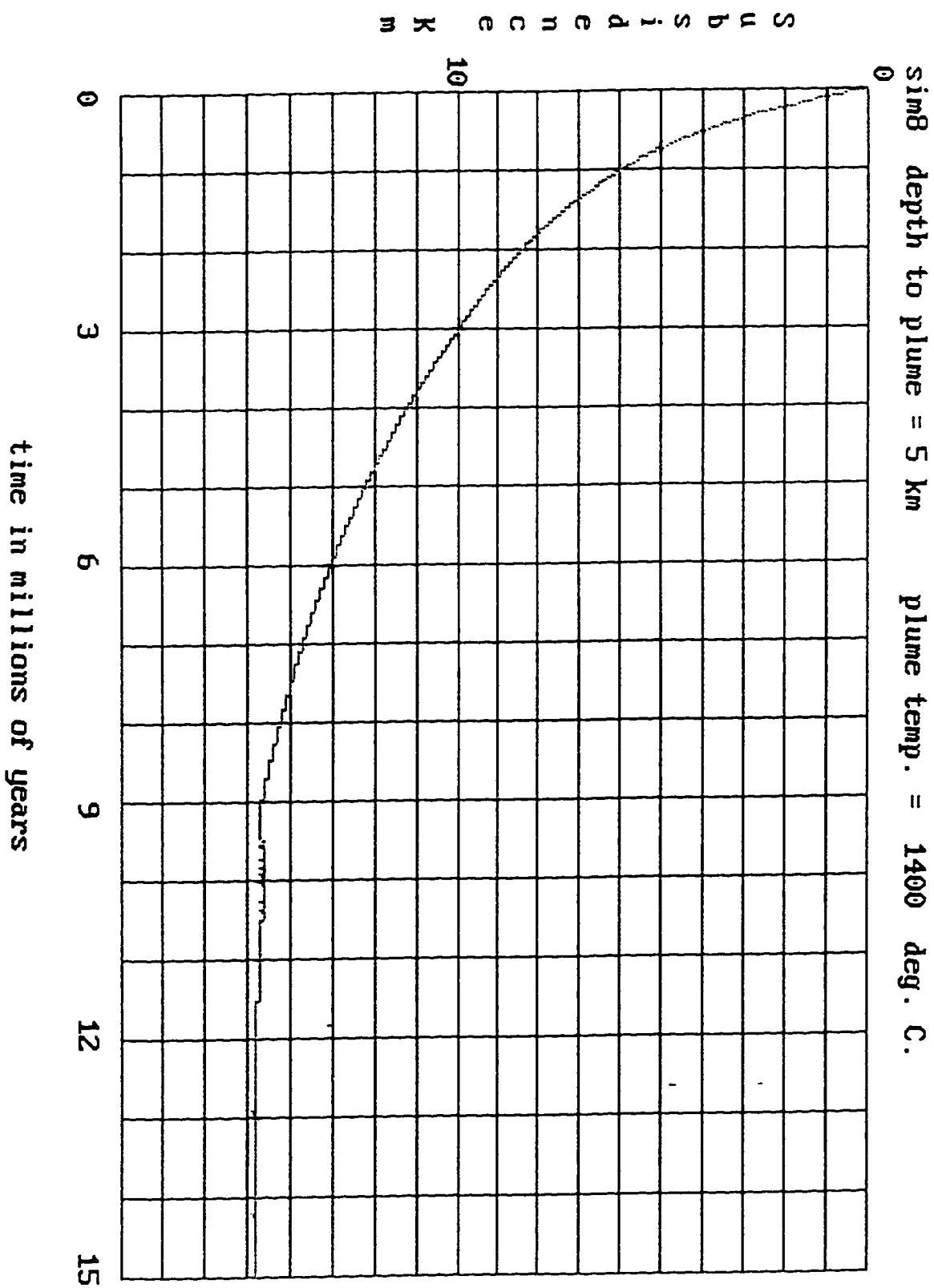


S u b s i d e n c e   K m

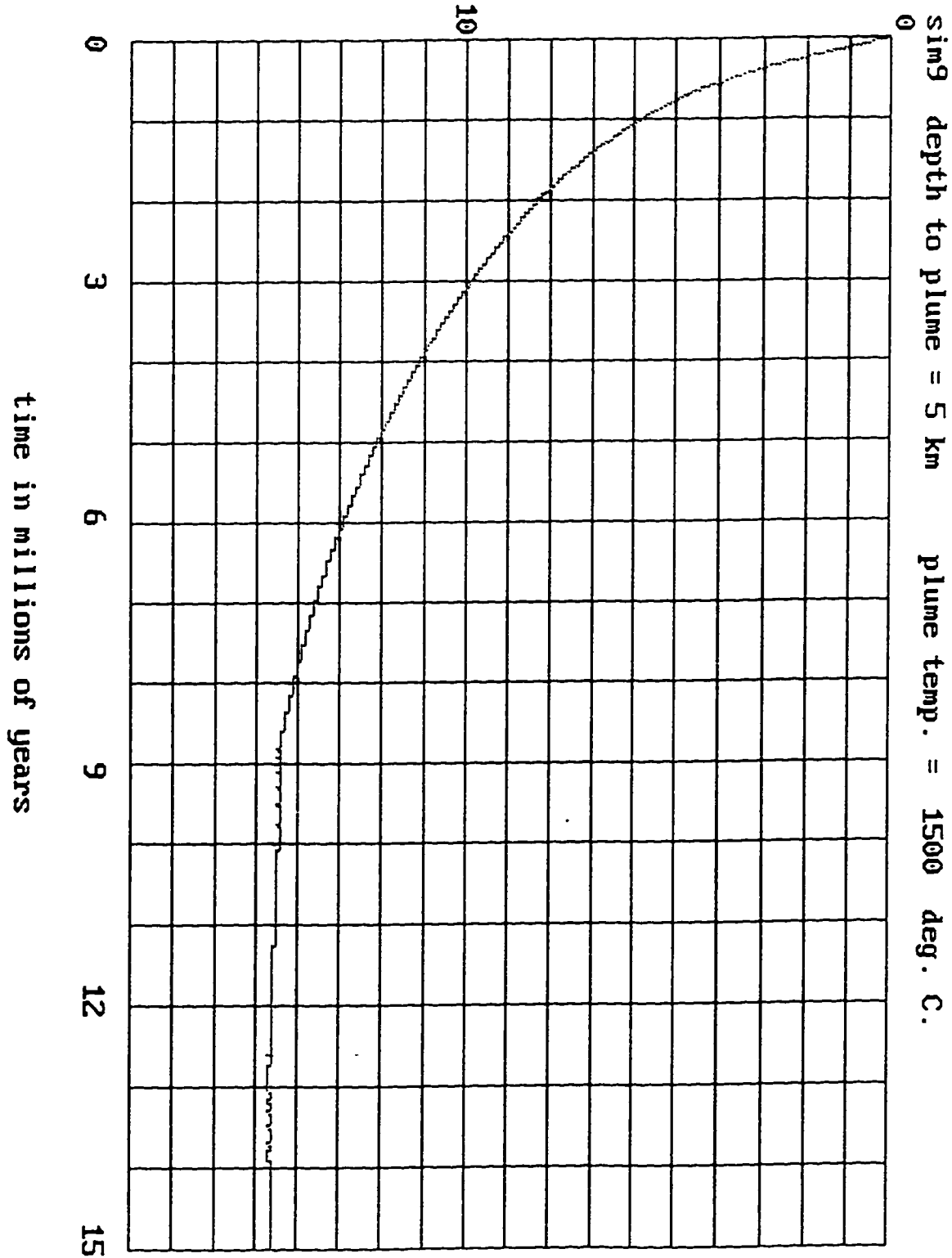


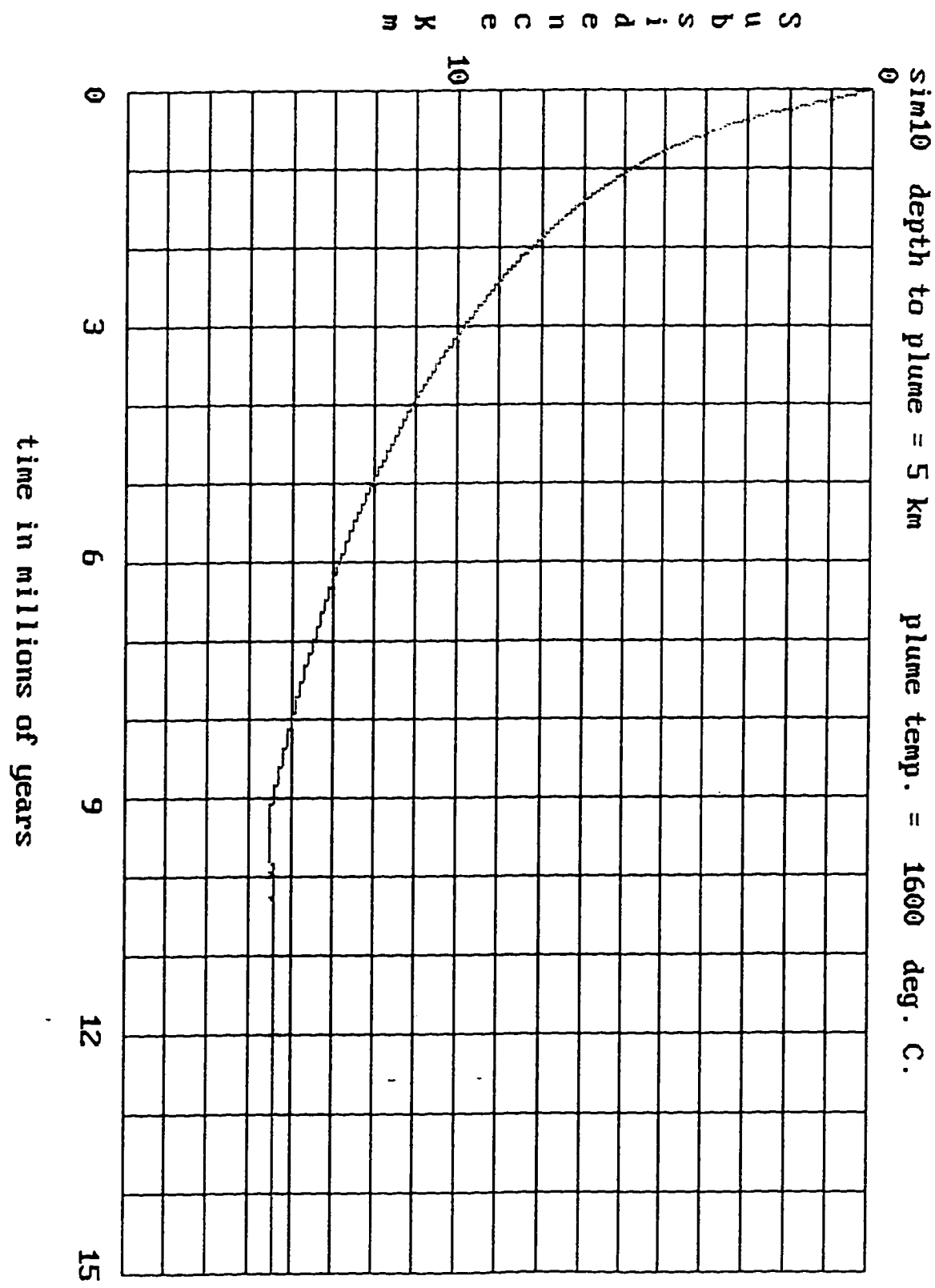


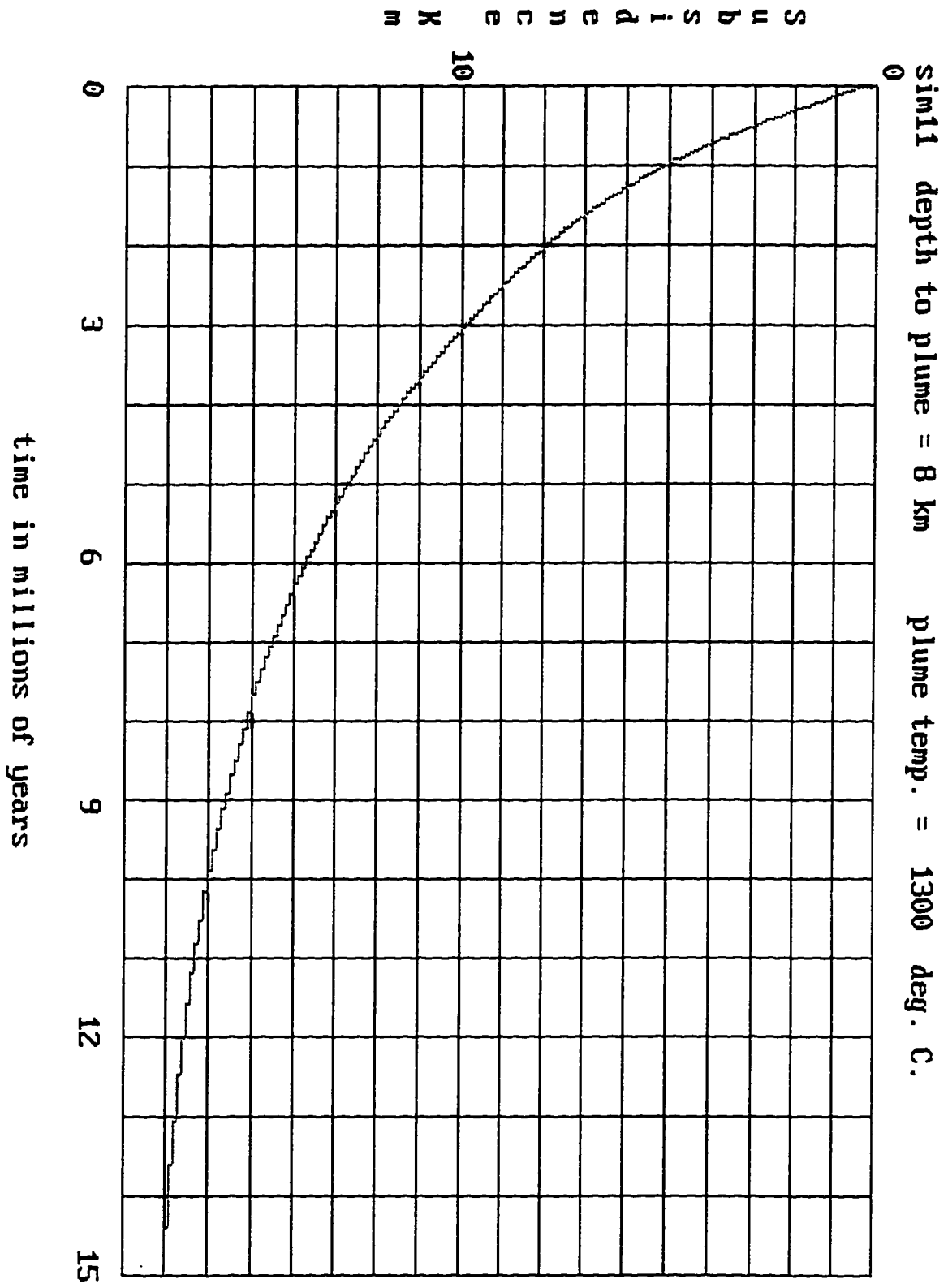


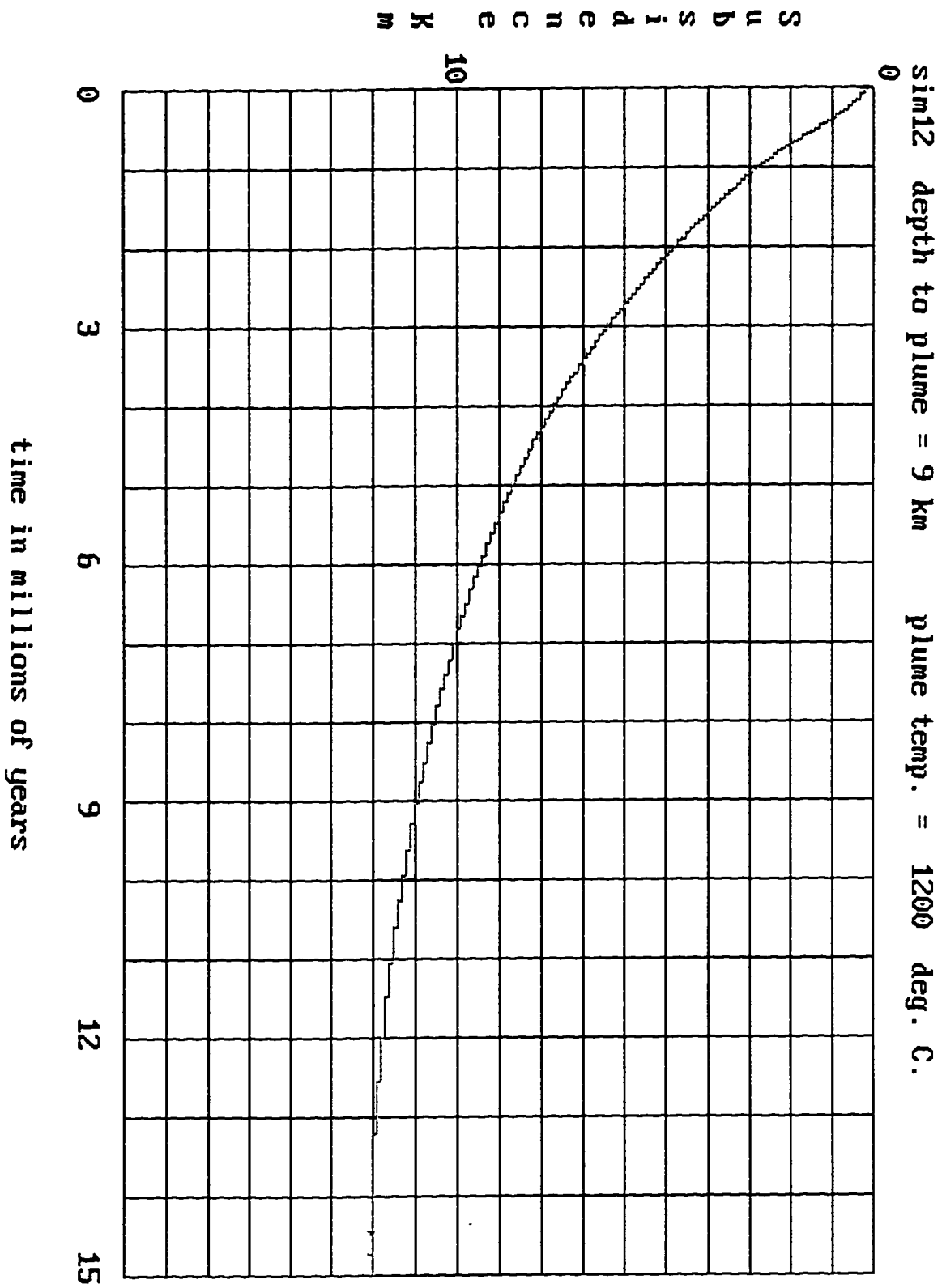


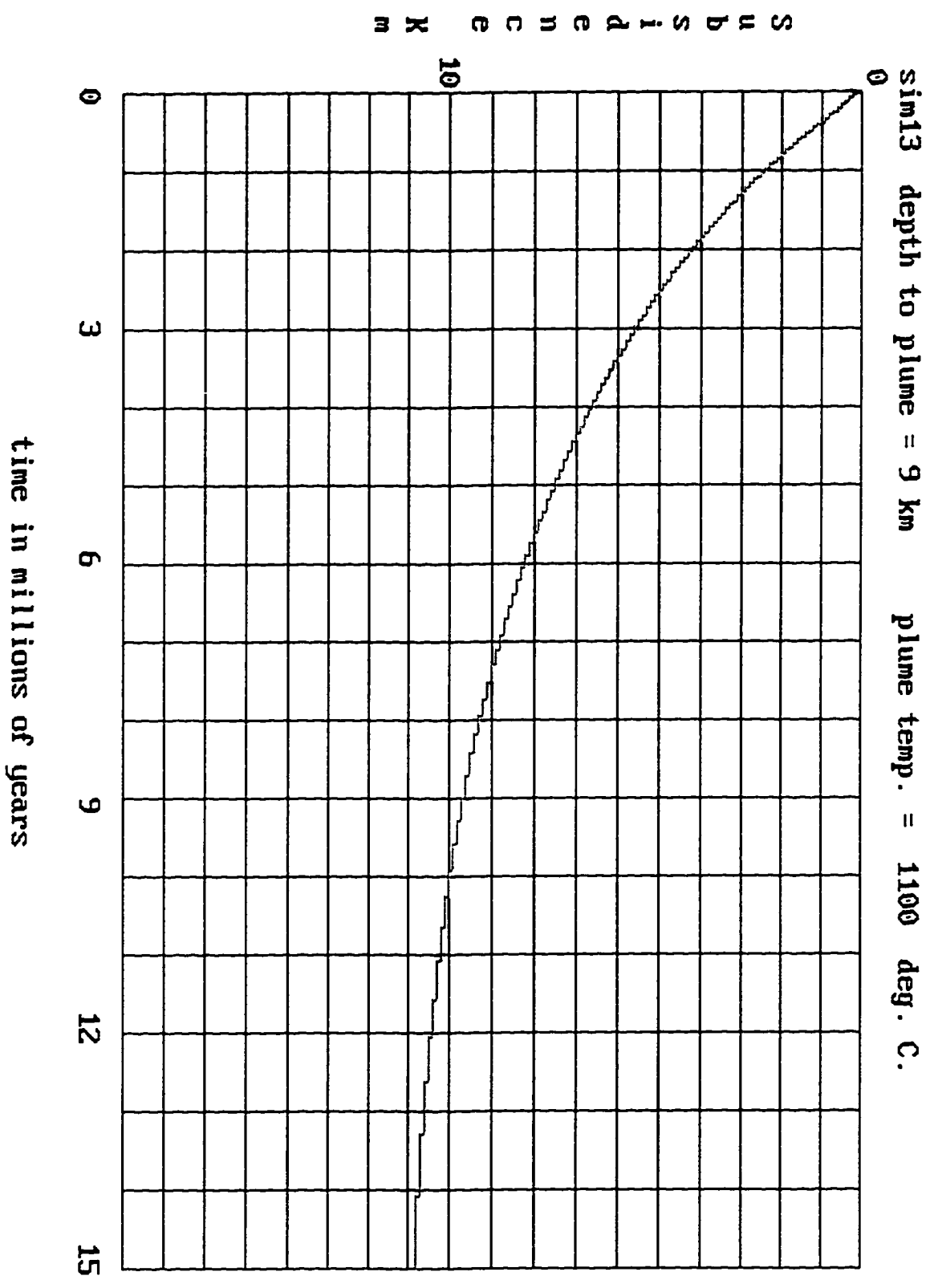
S u b s i d e n c e   K m

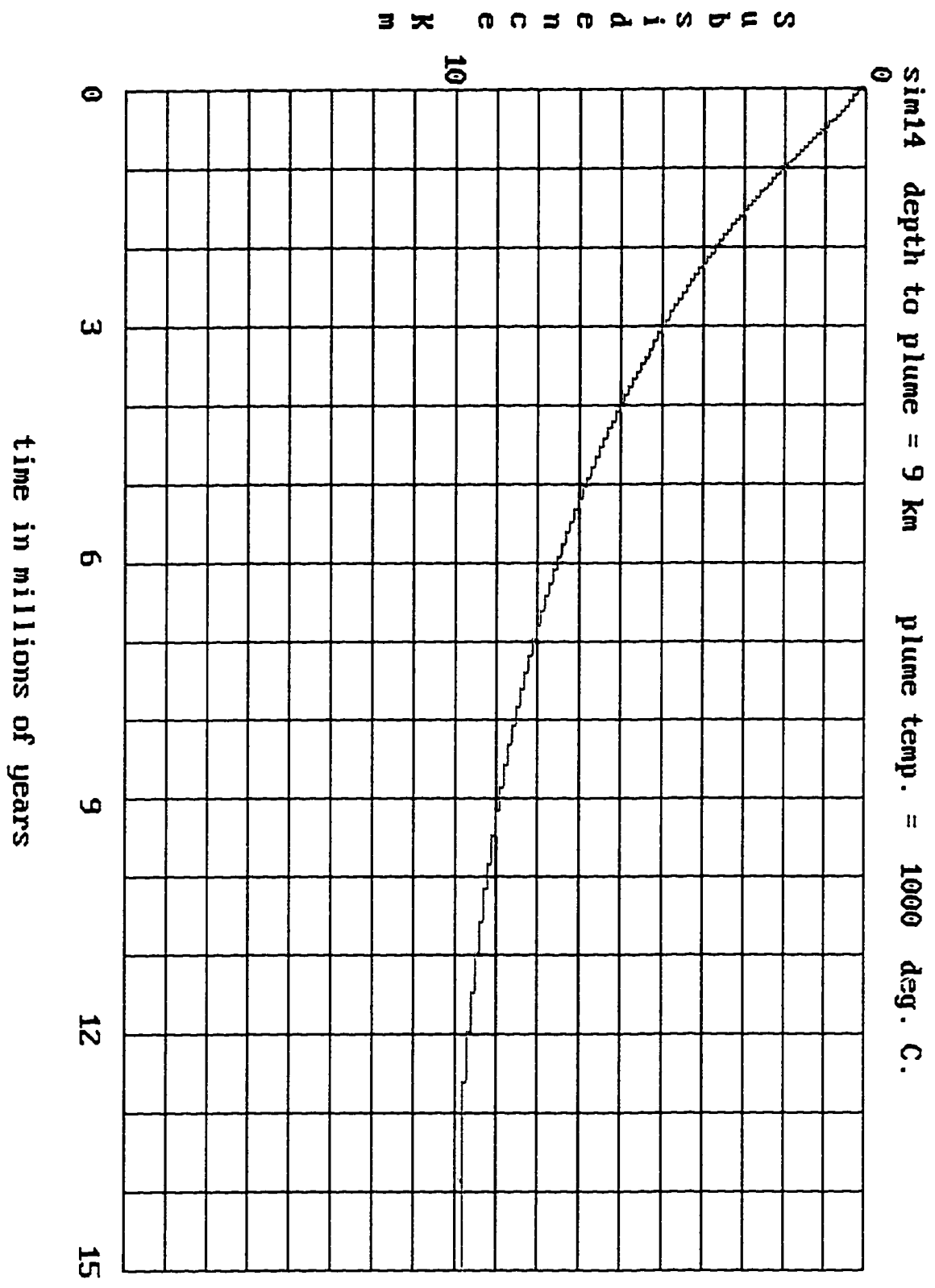


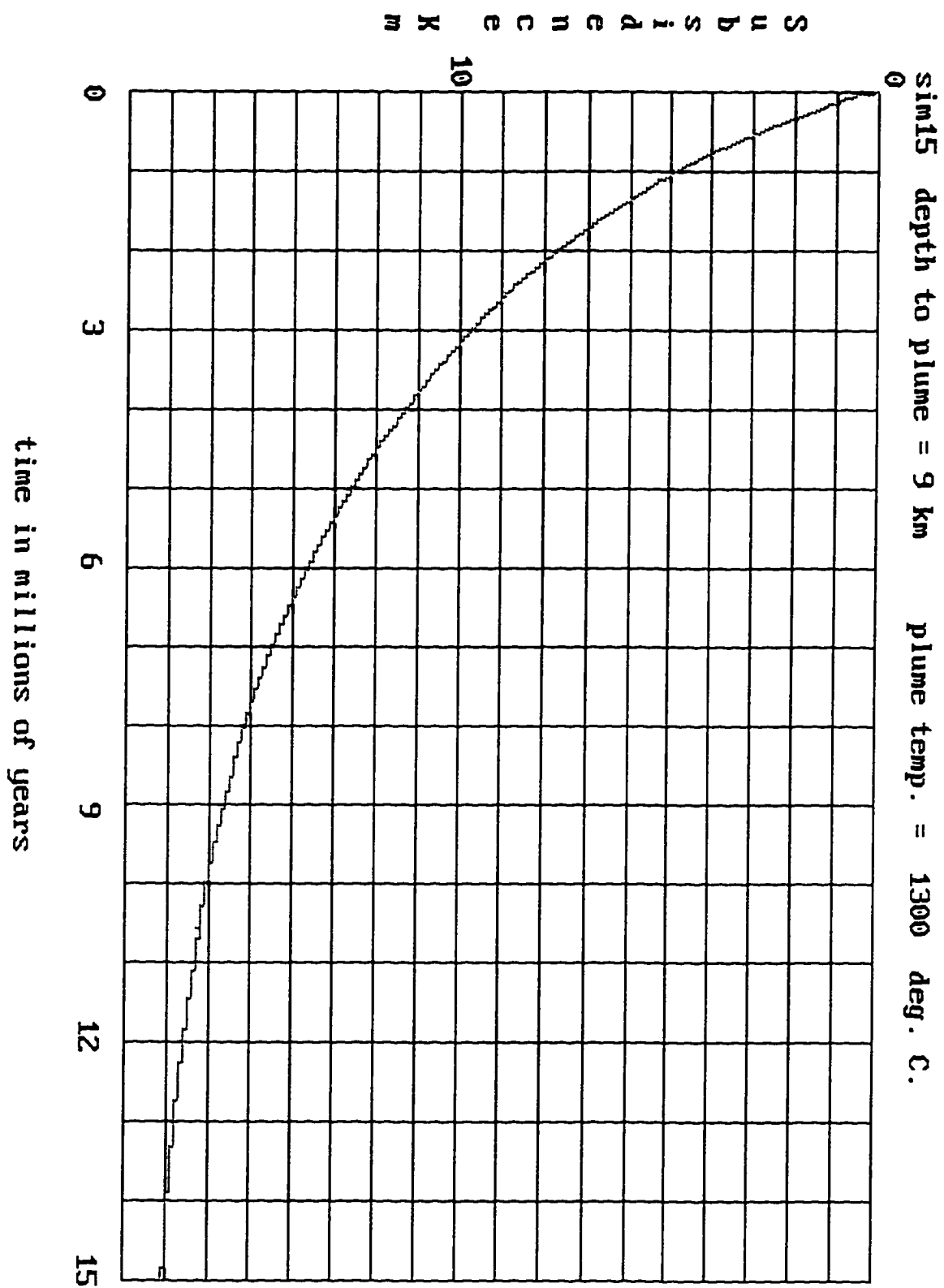


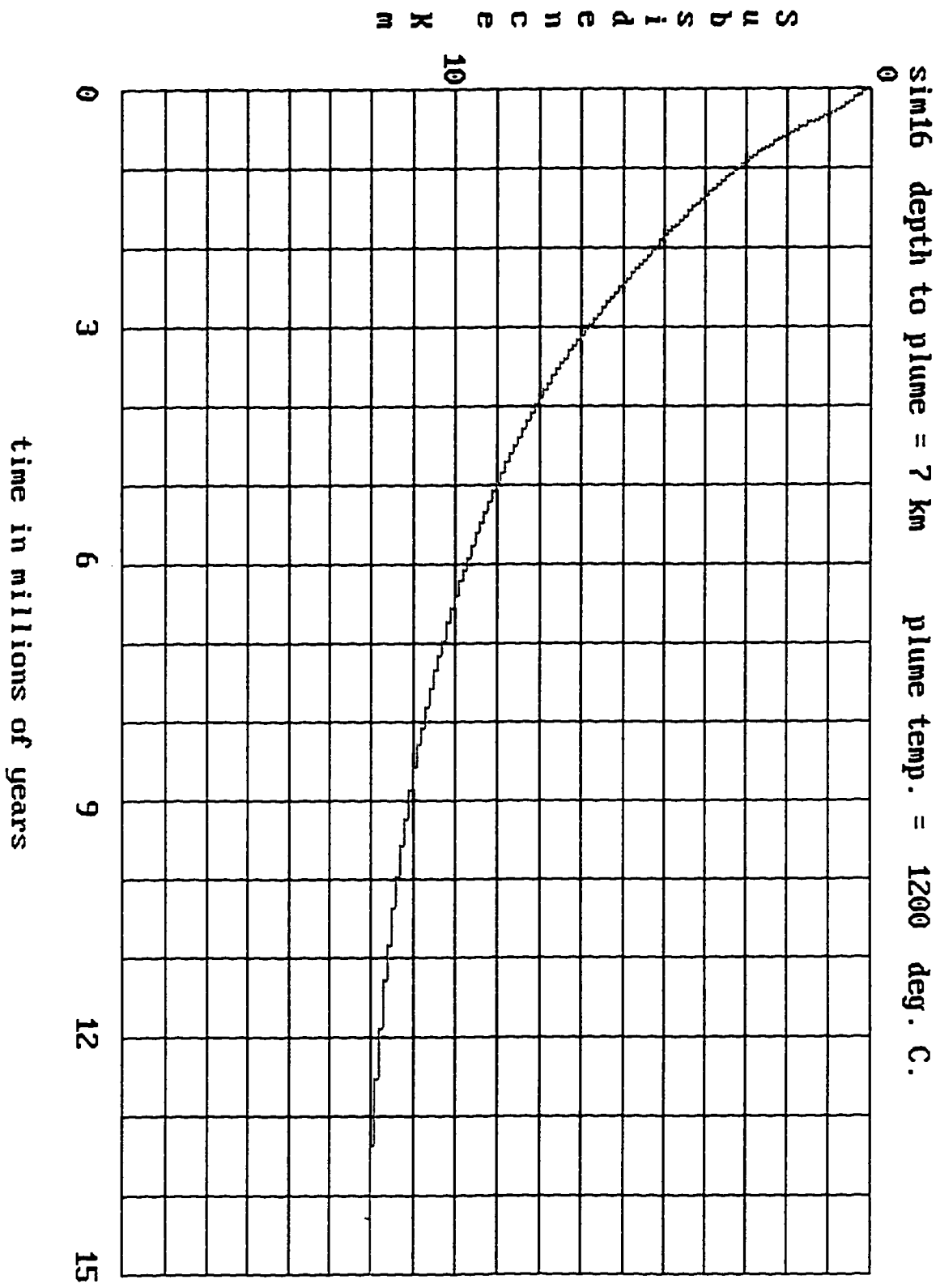


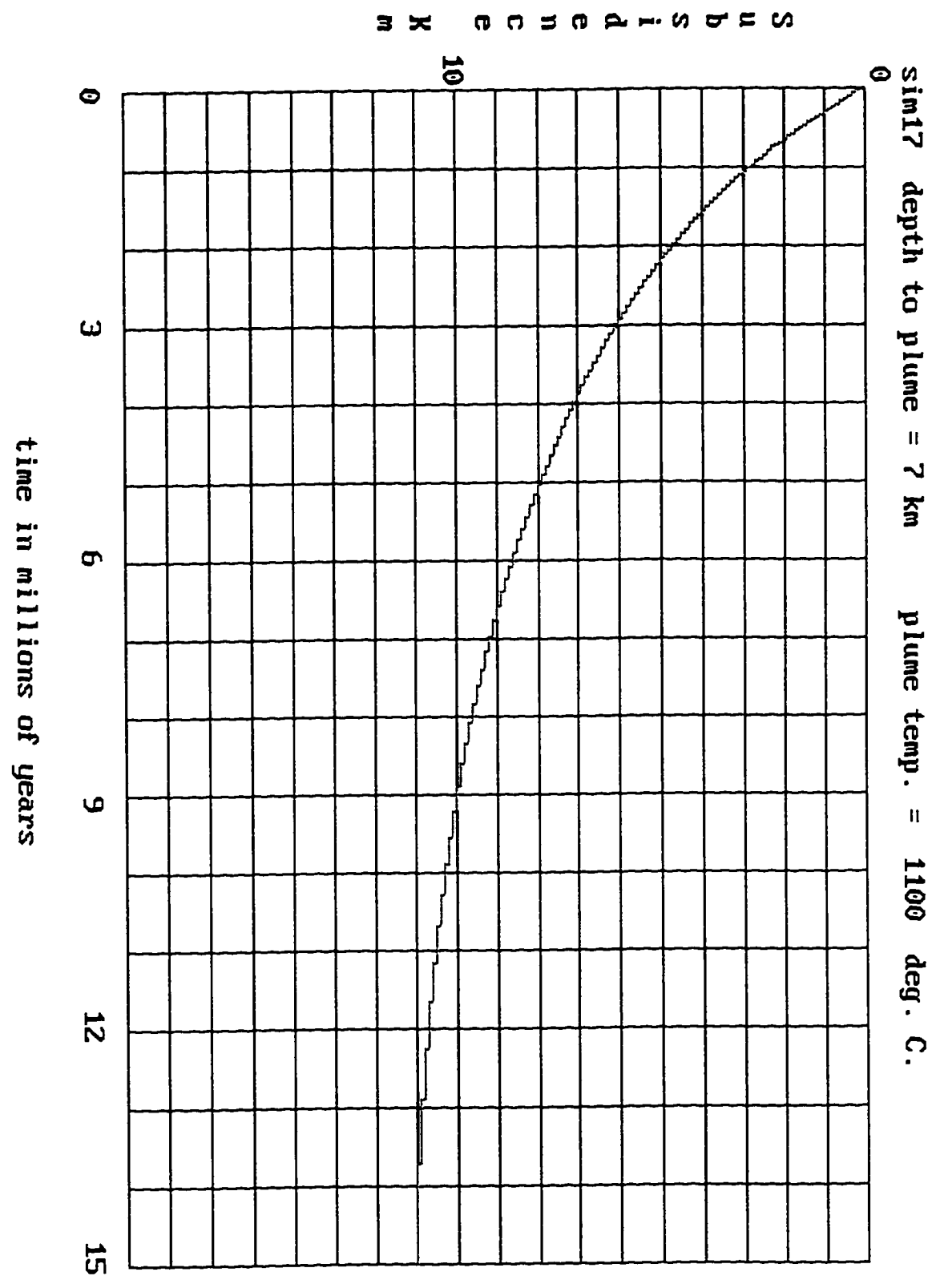


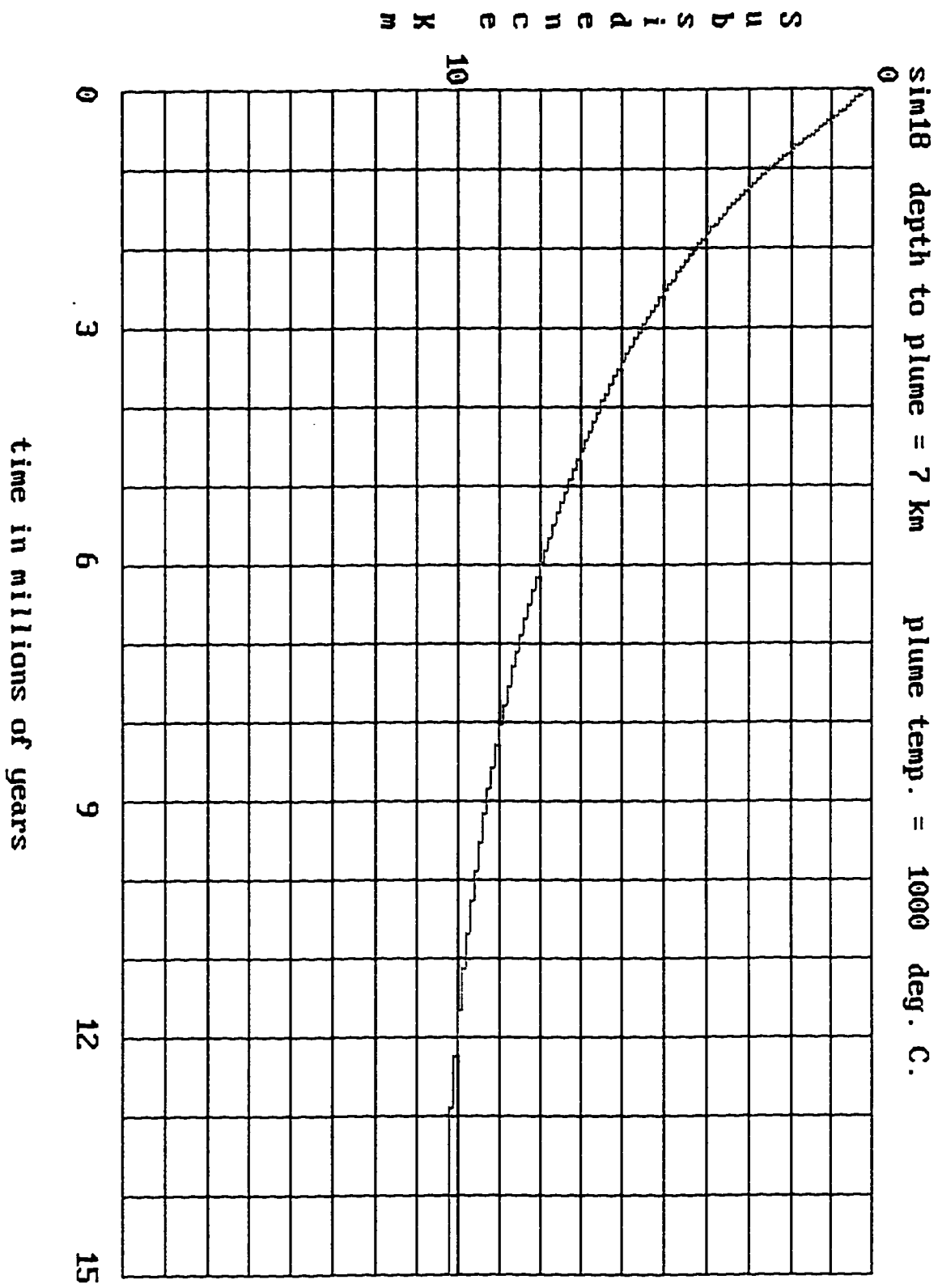


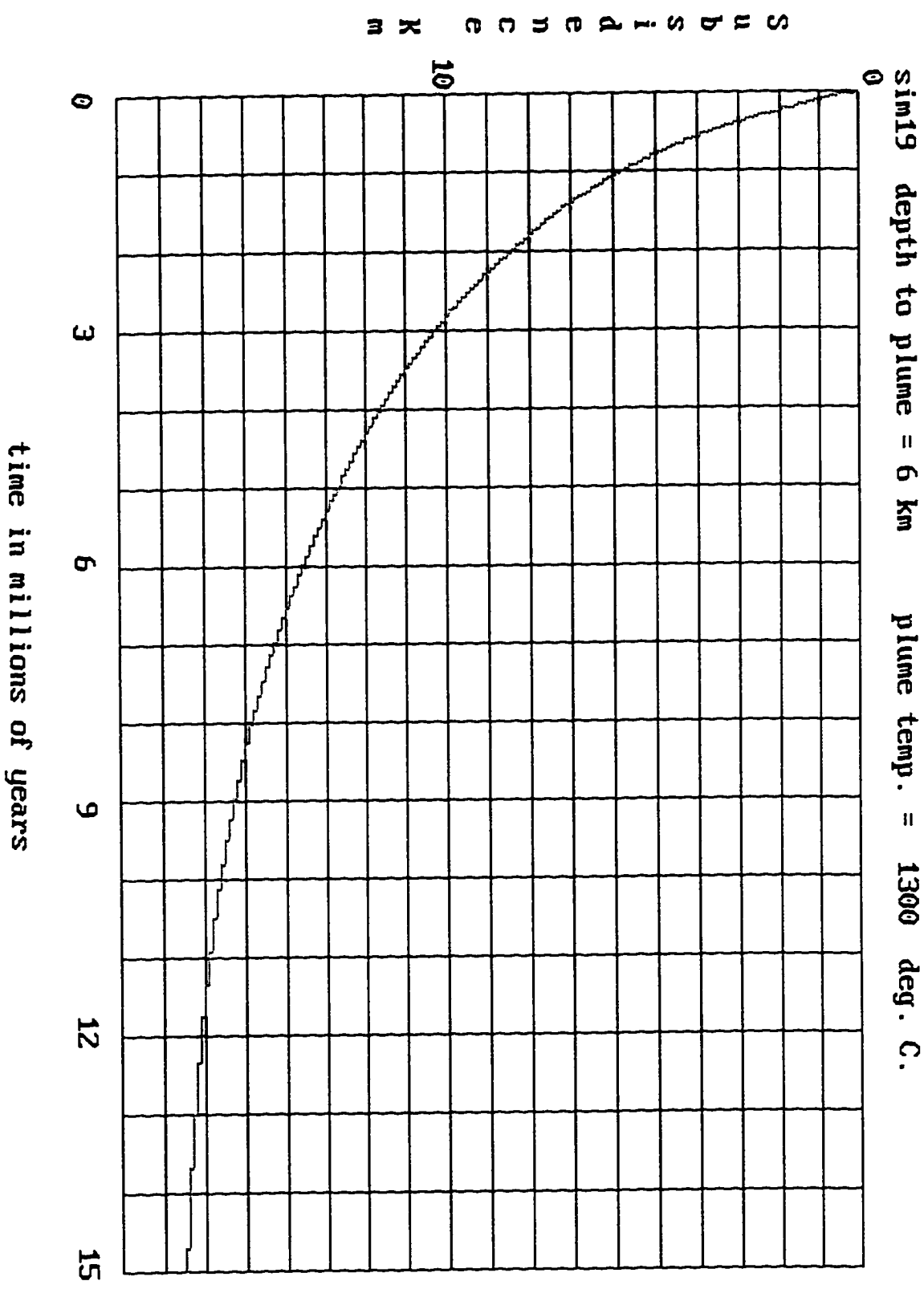


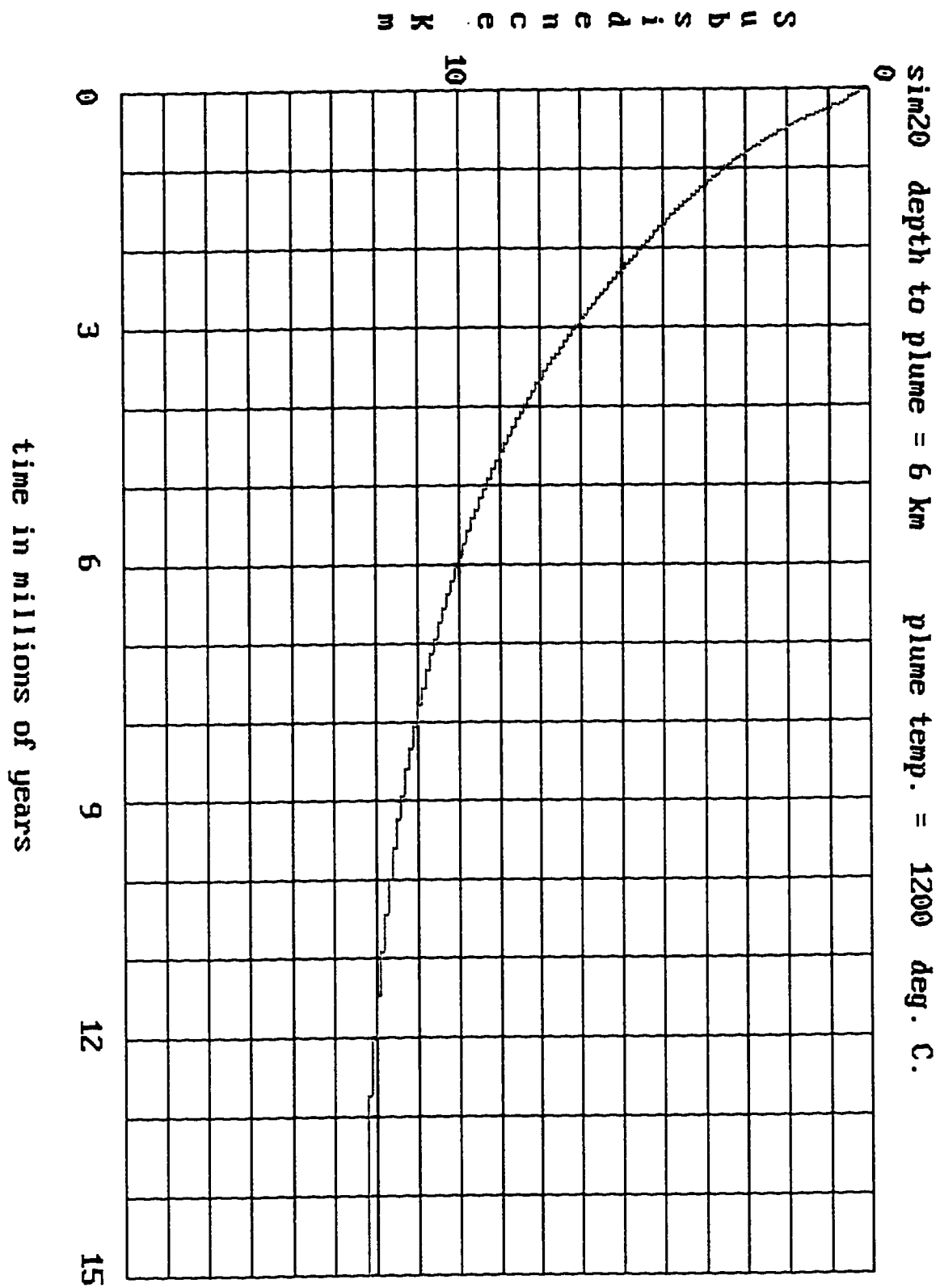


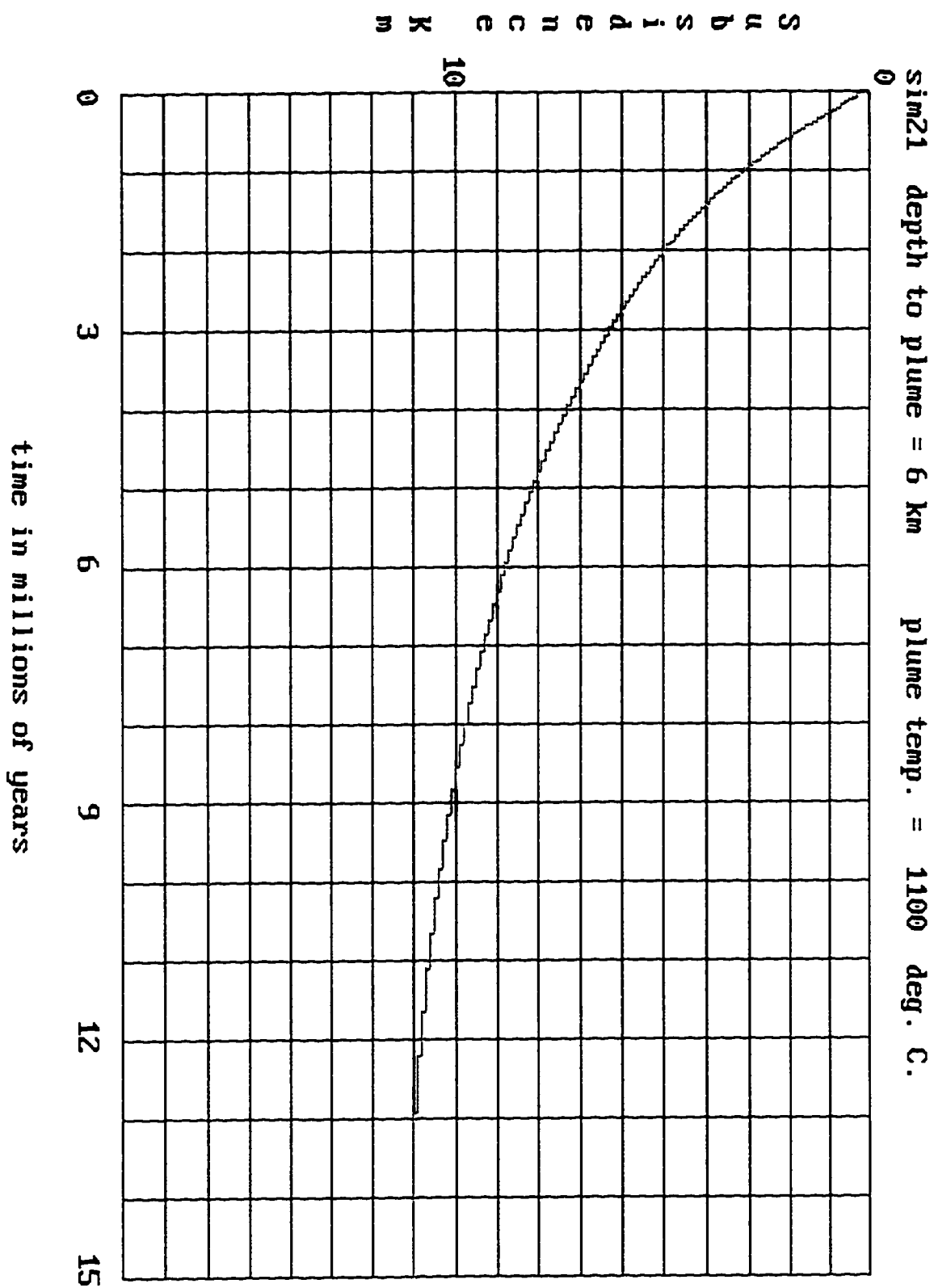


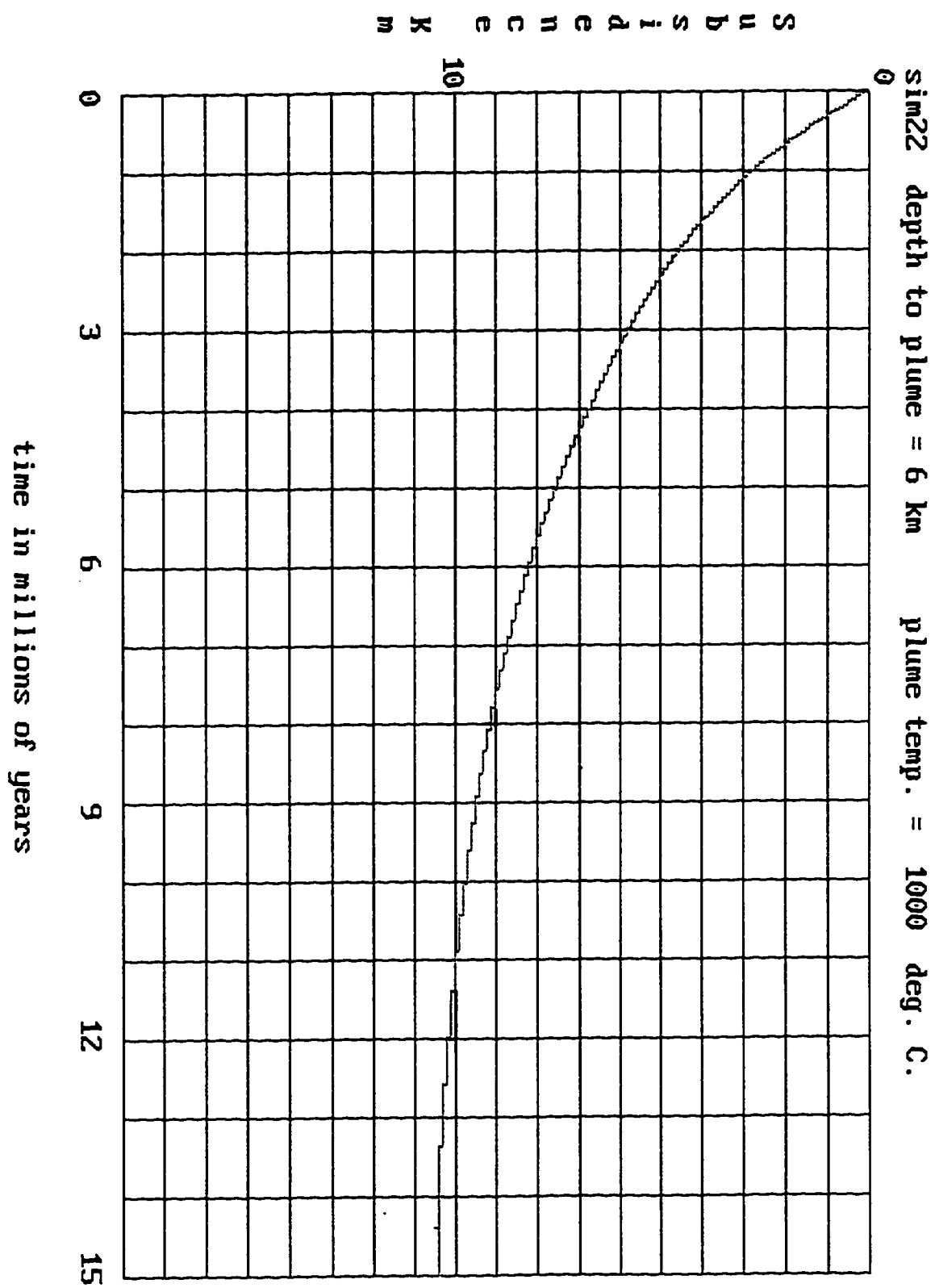


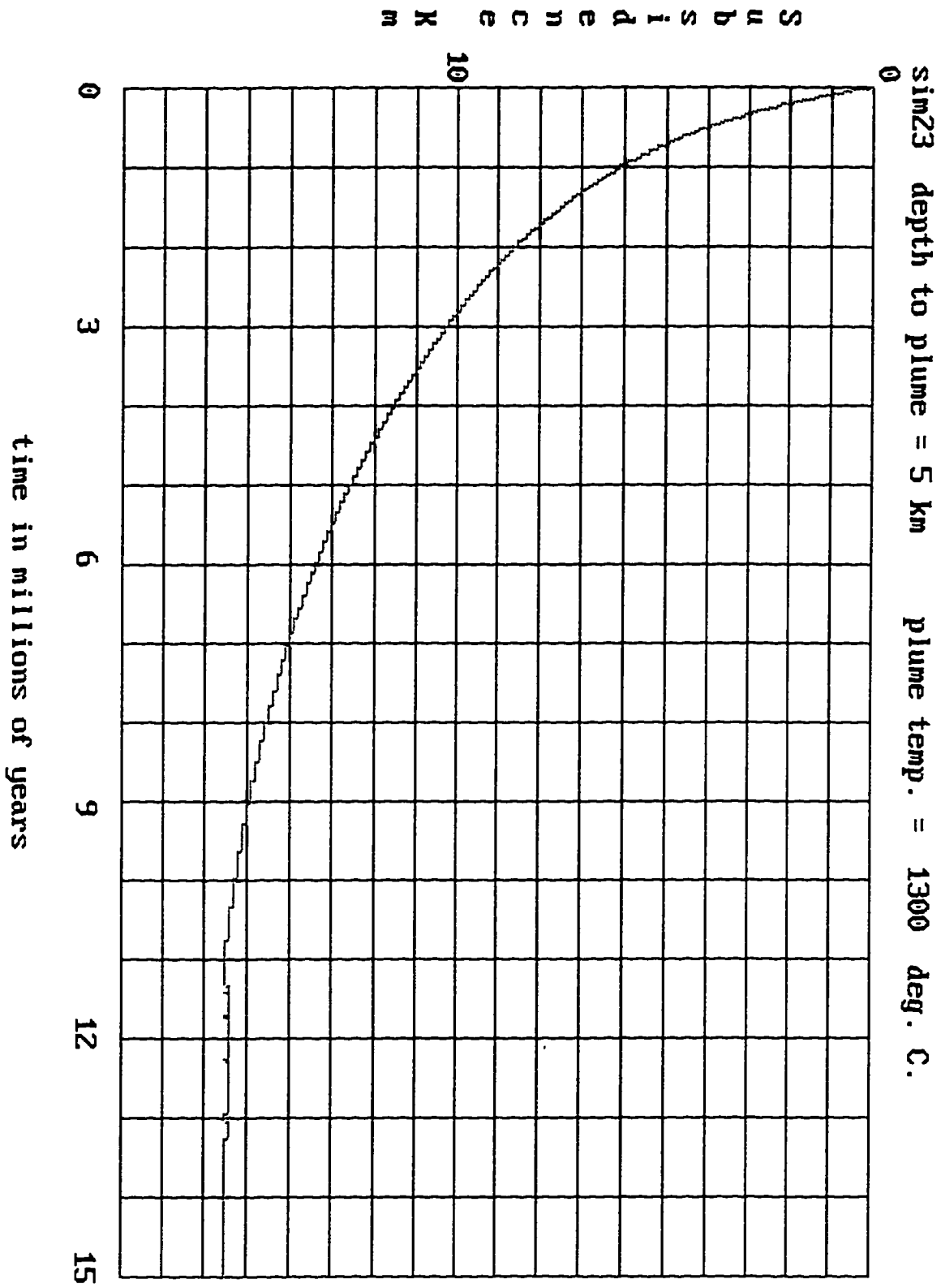


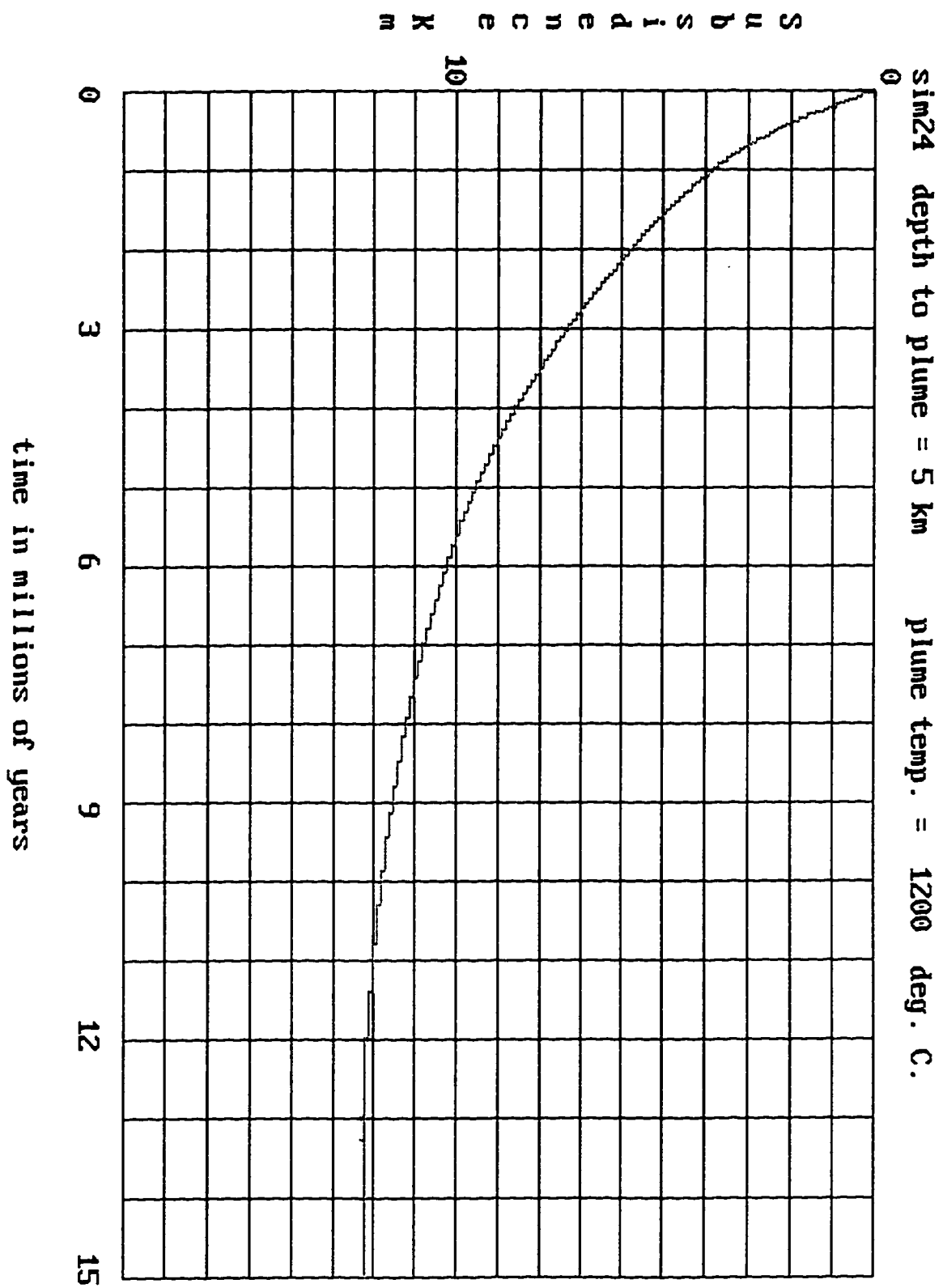


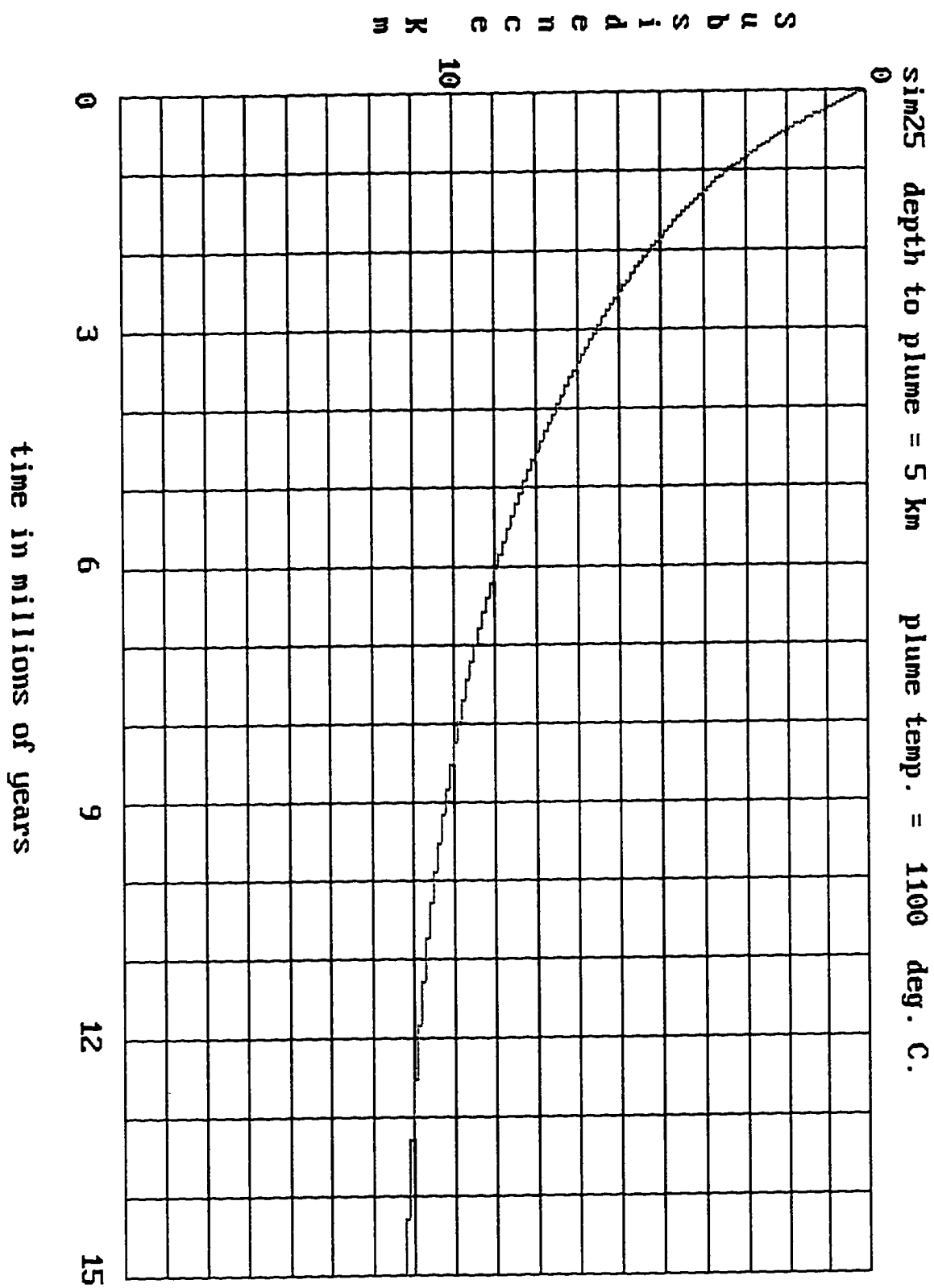


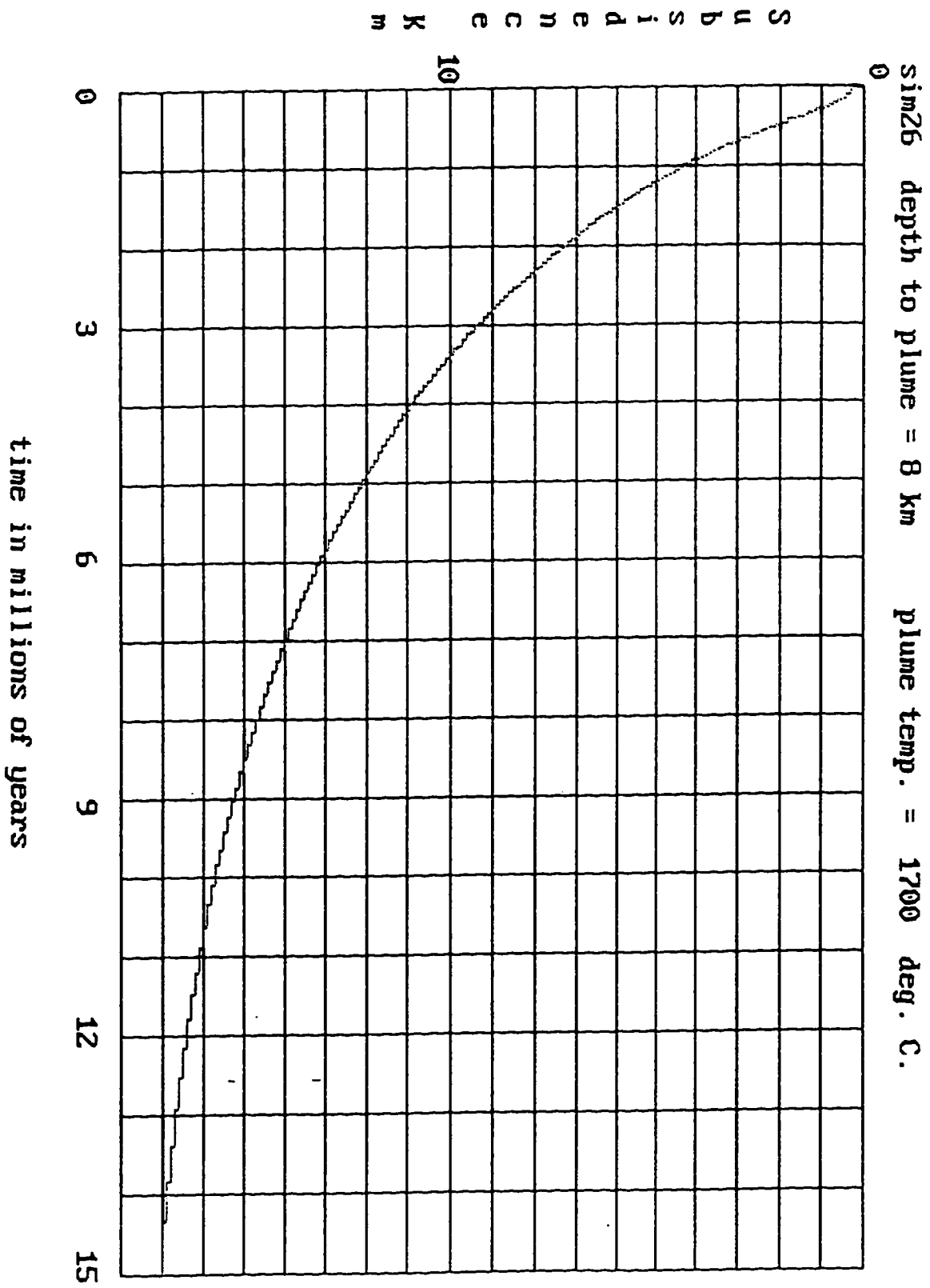


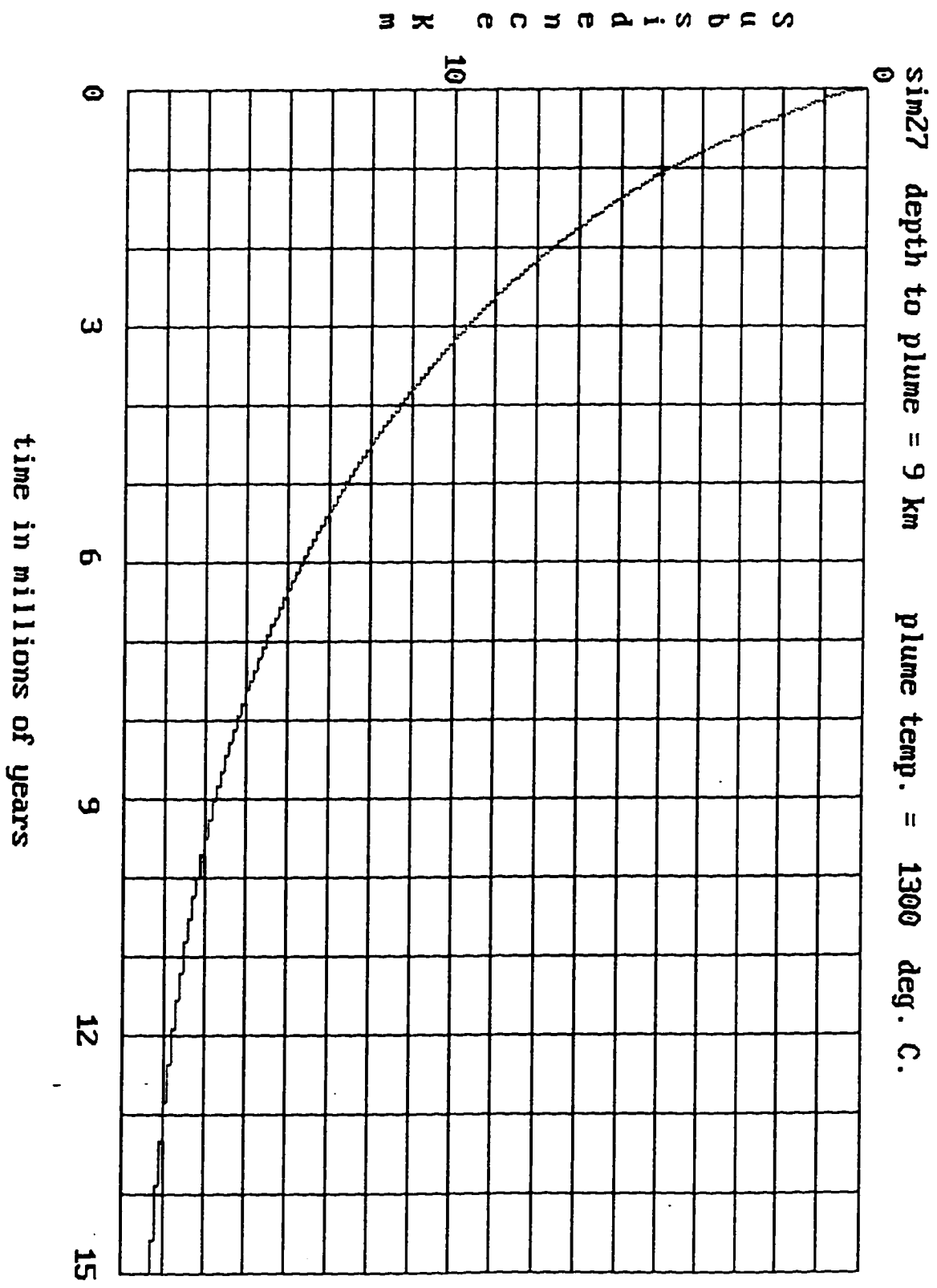


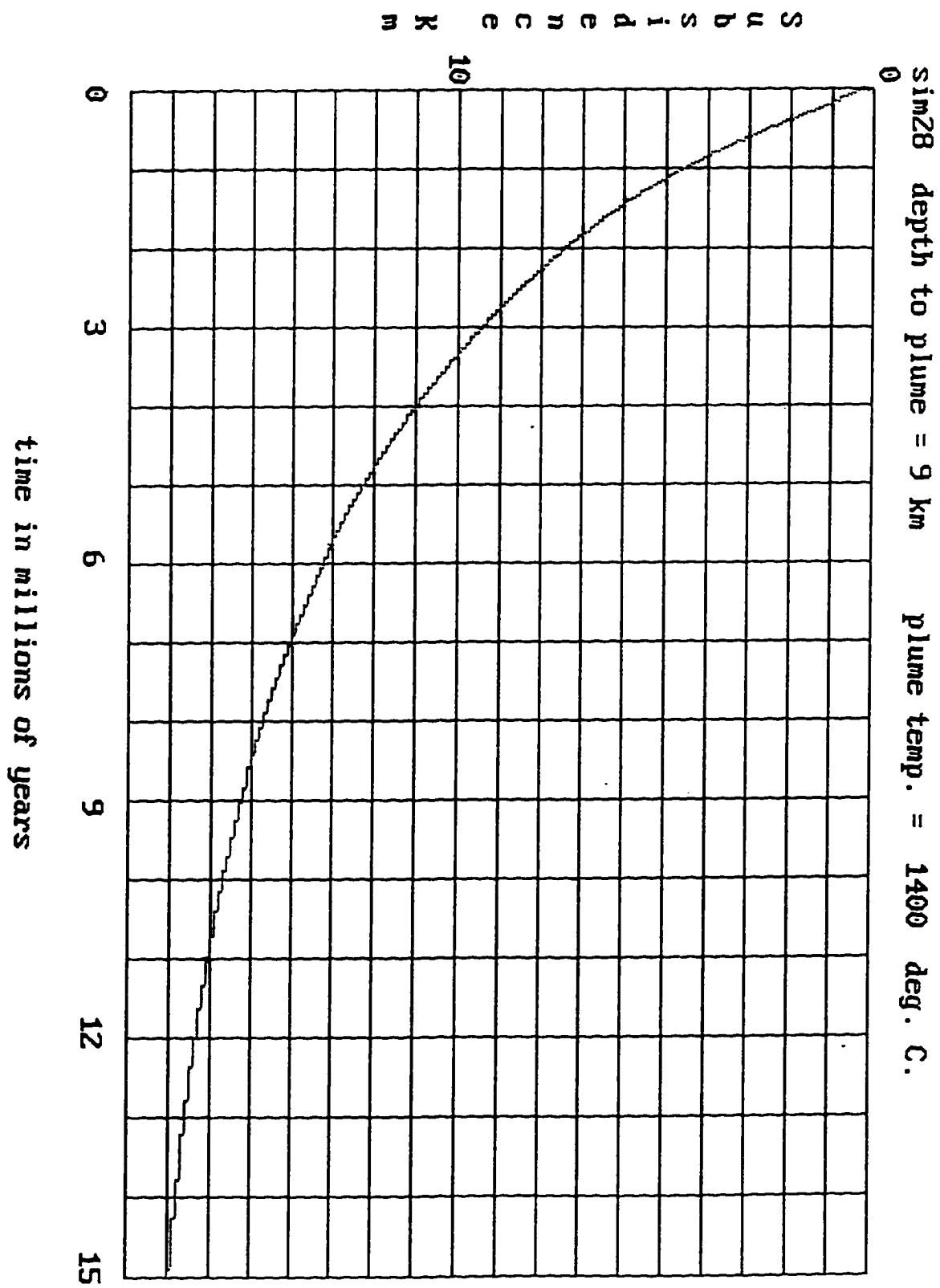


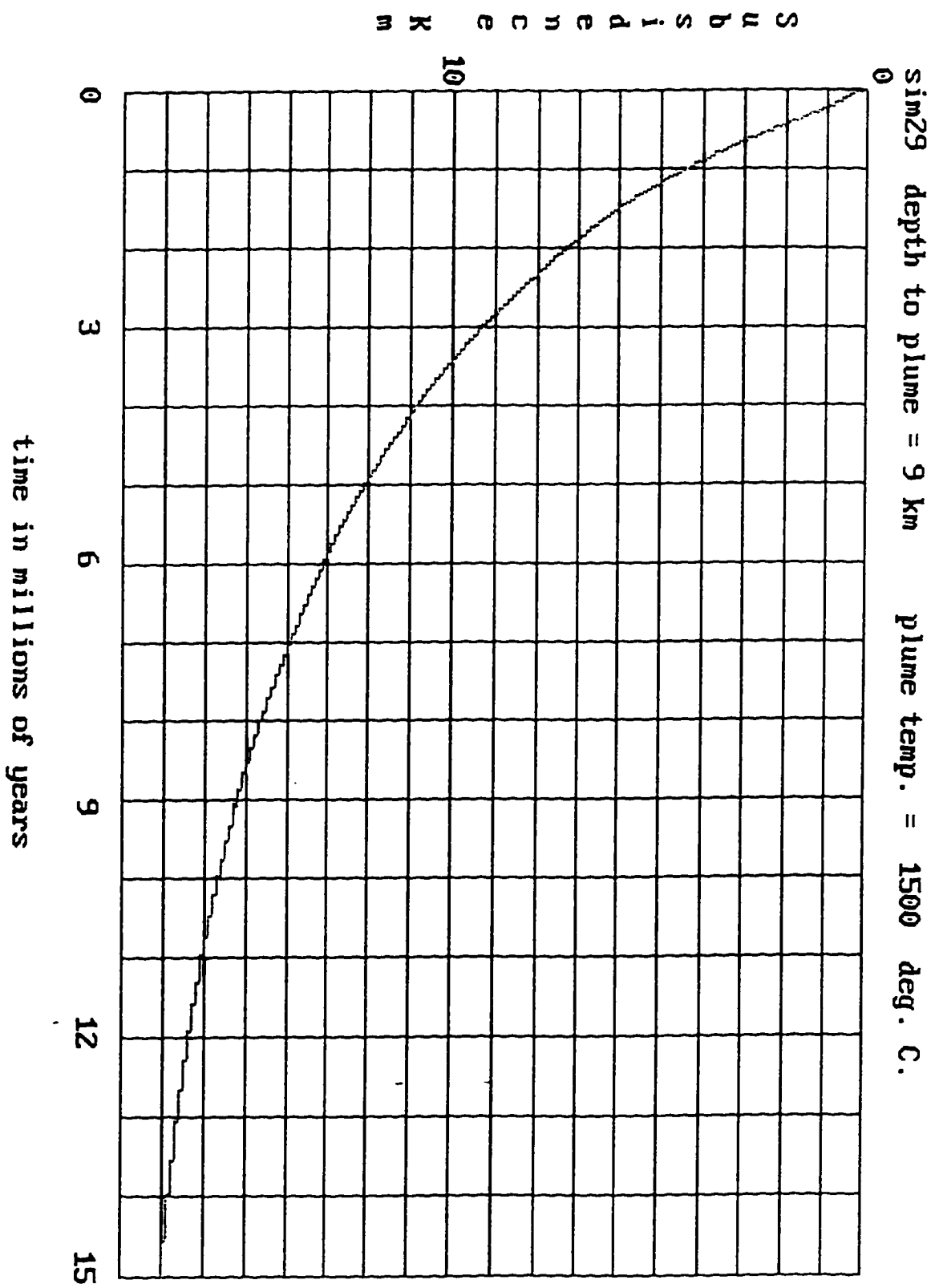




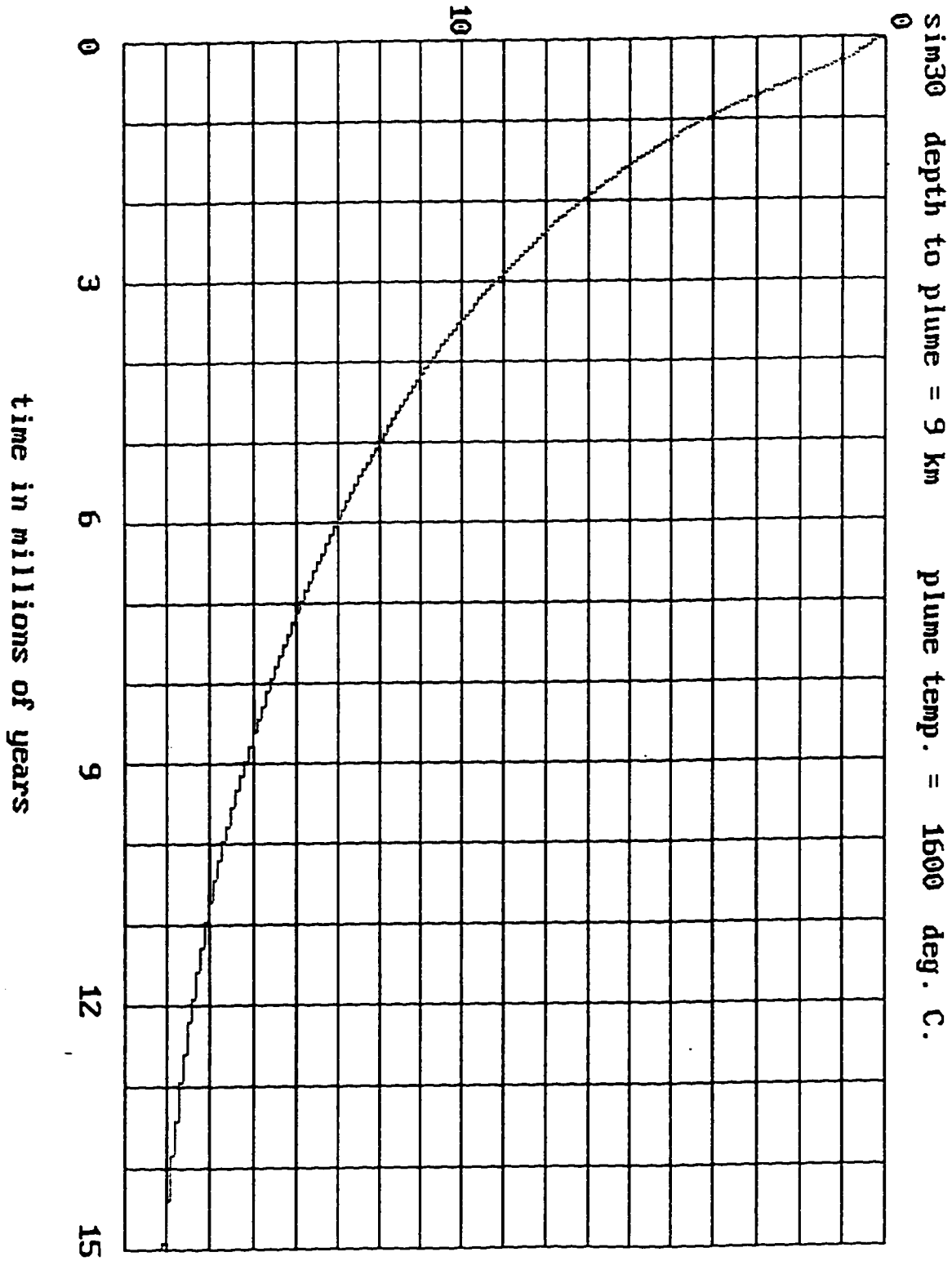


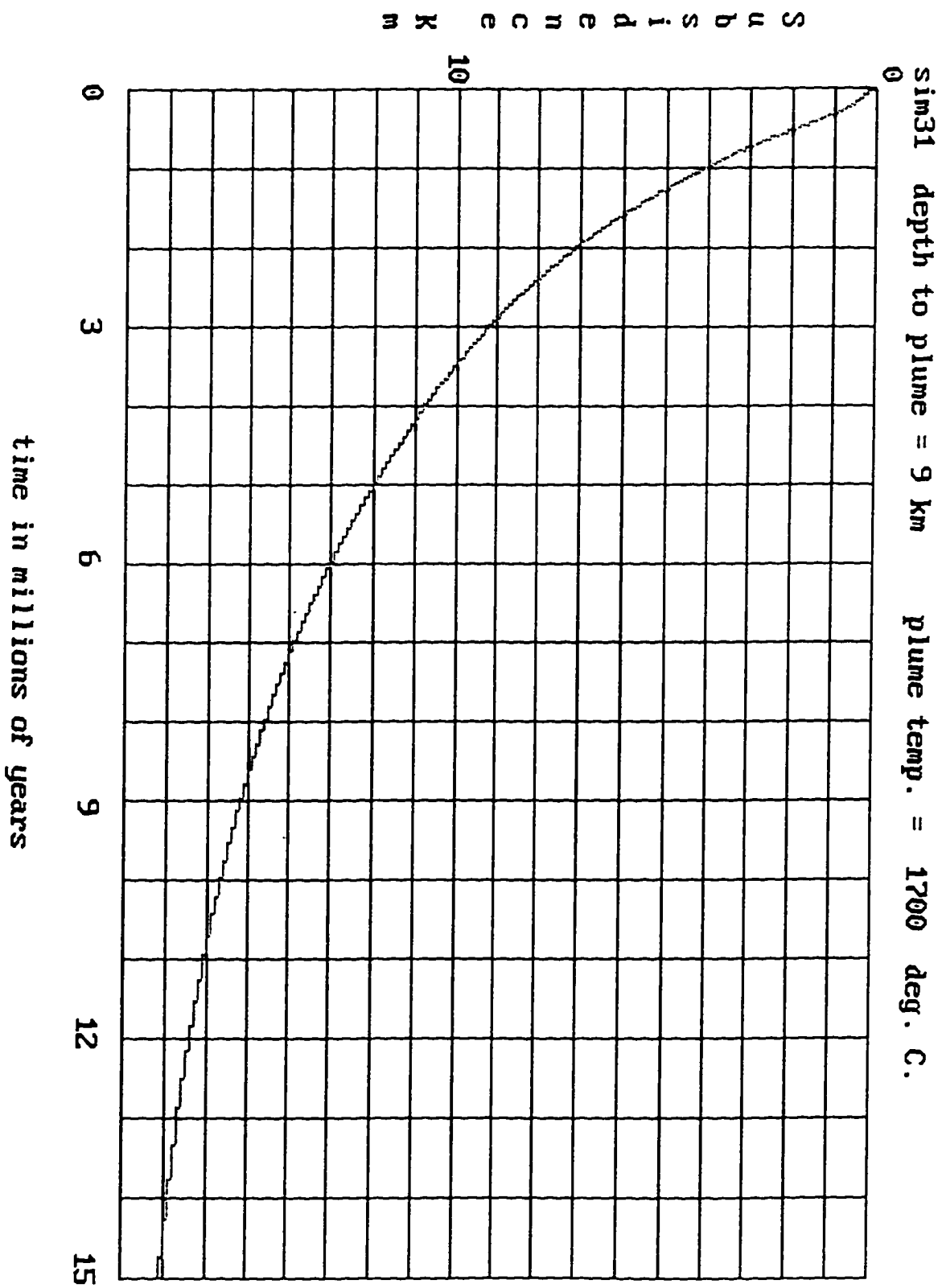




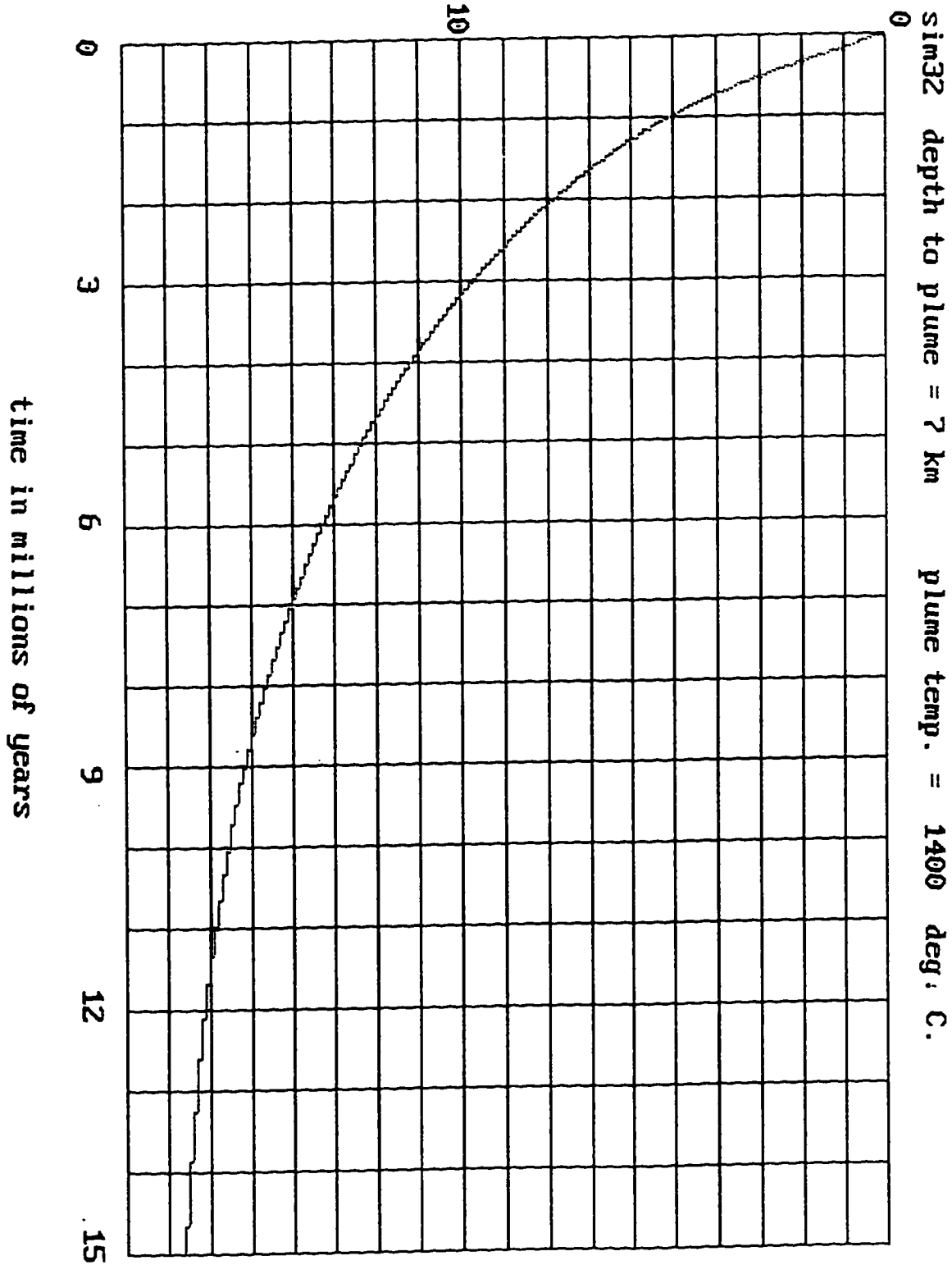


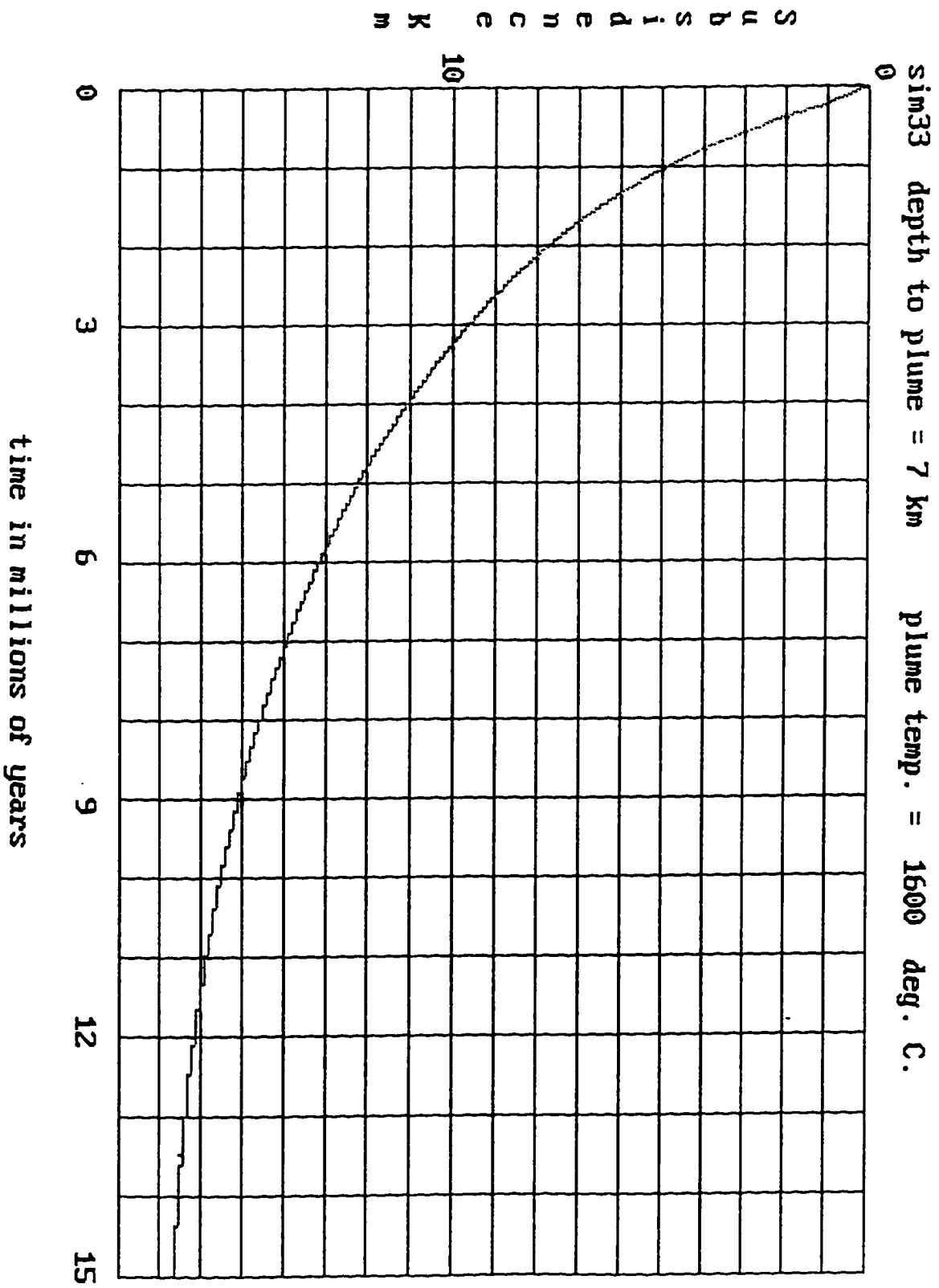
S u b s i d e n c e  
K m

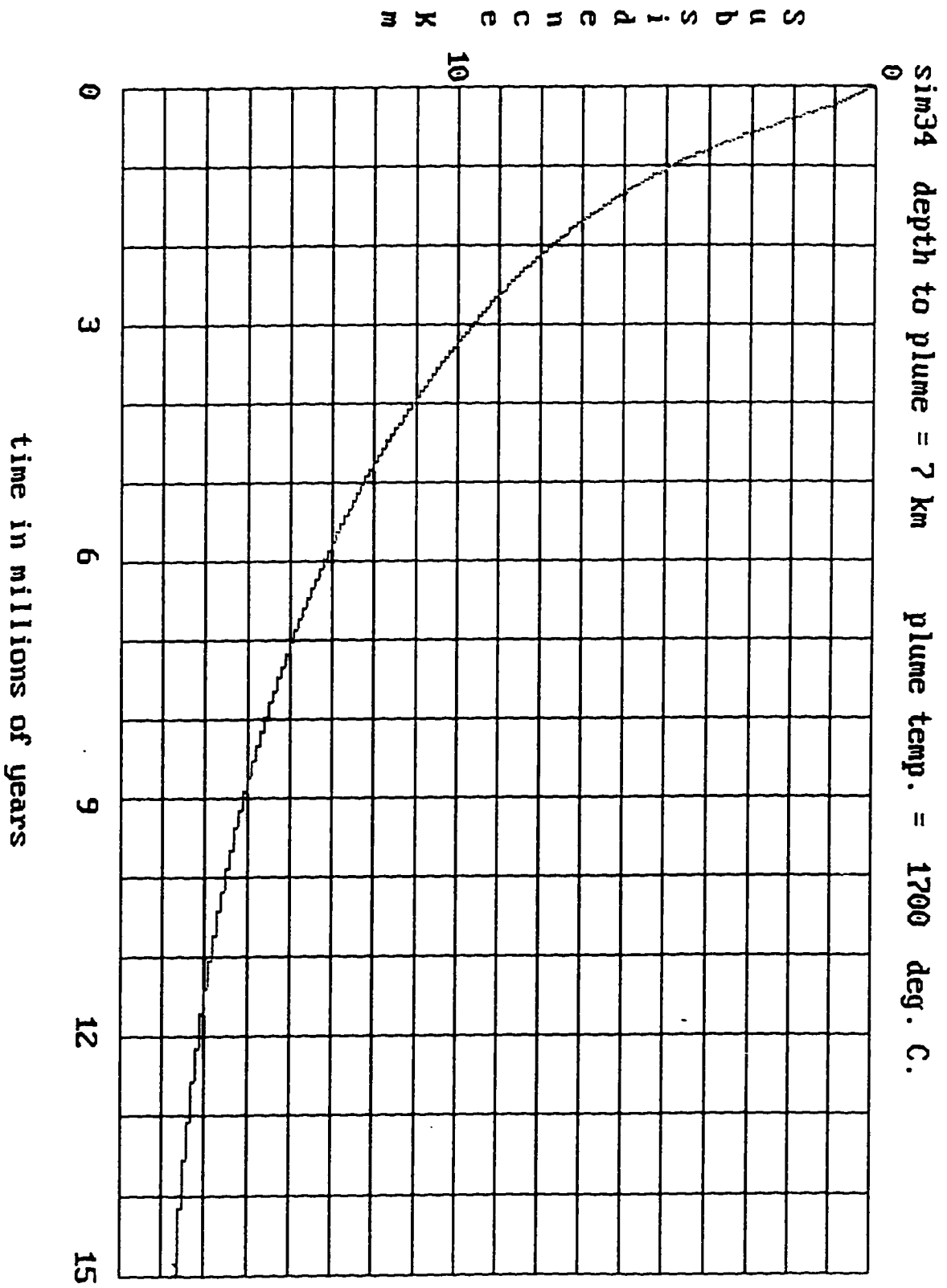


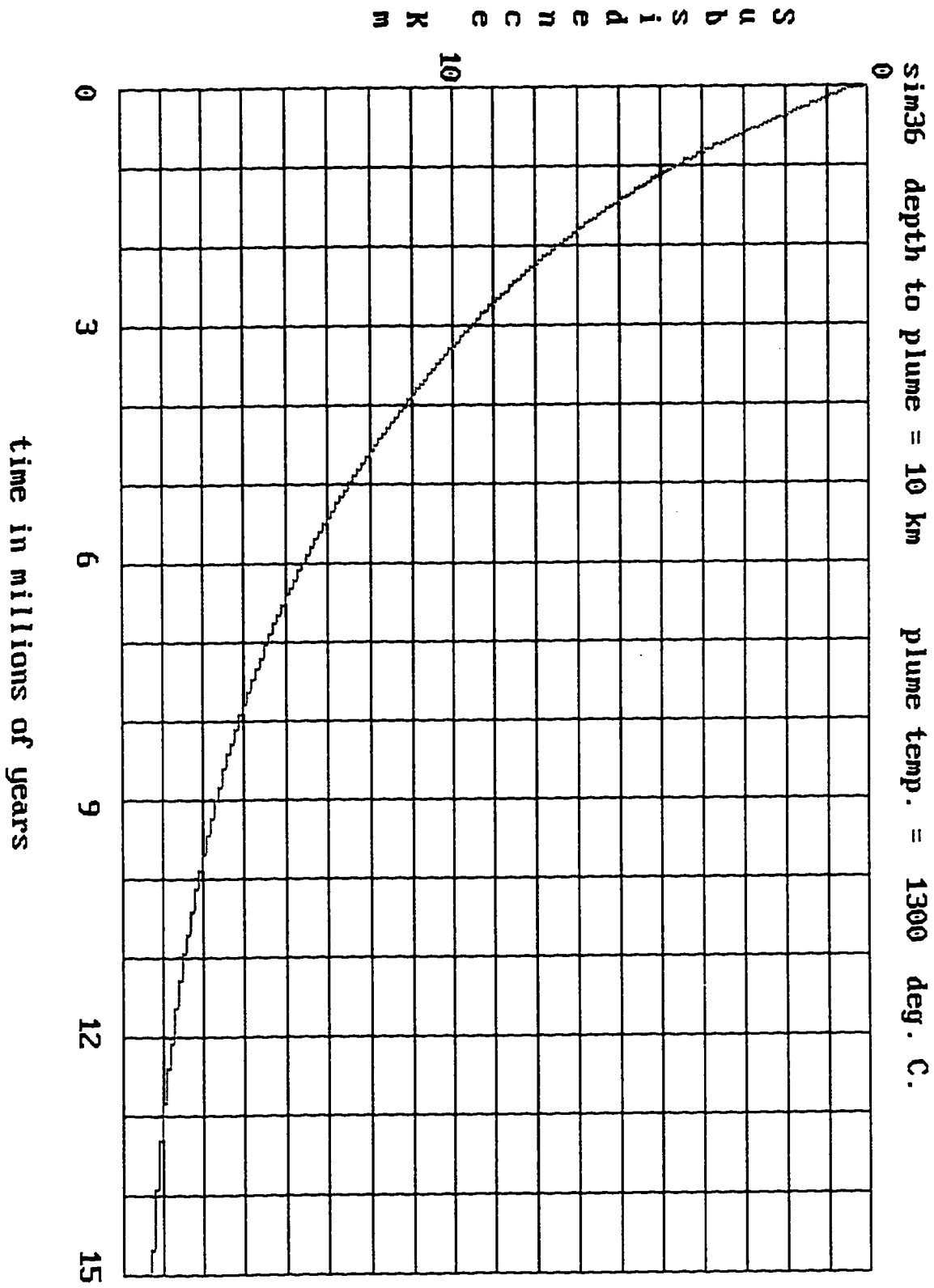


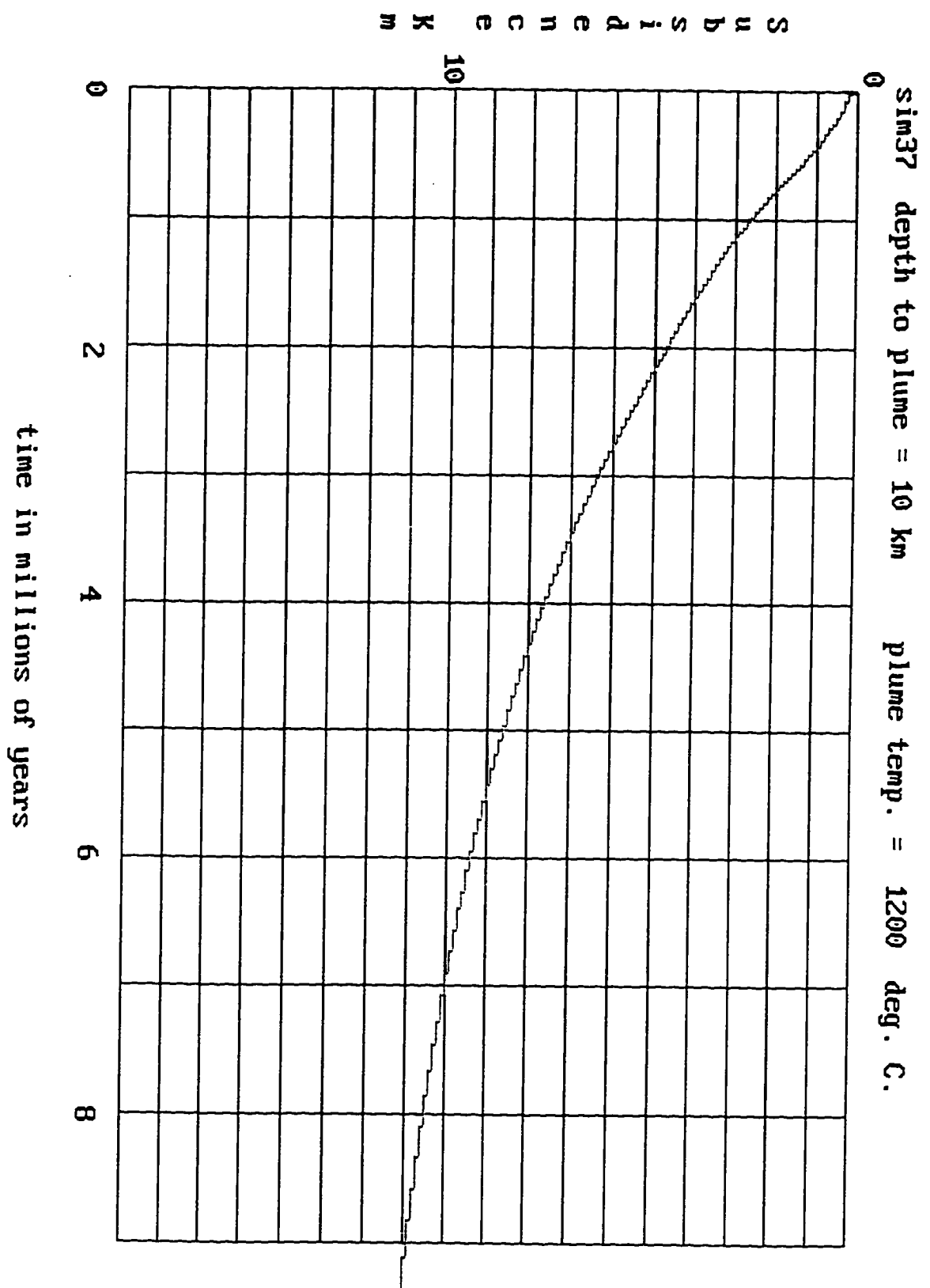
S u b s i d e n c e  
K m



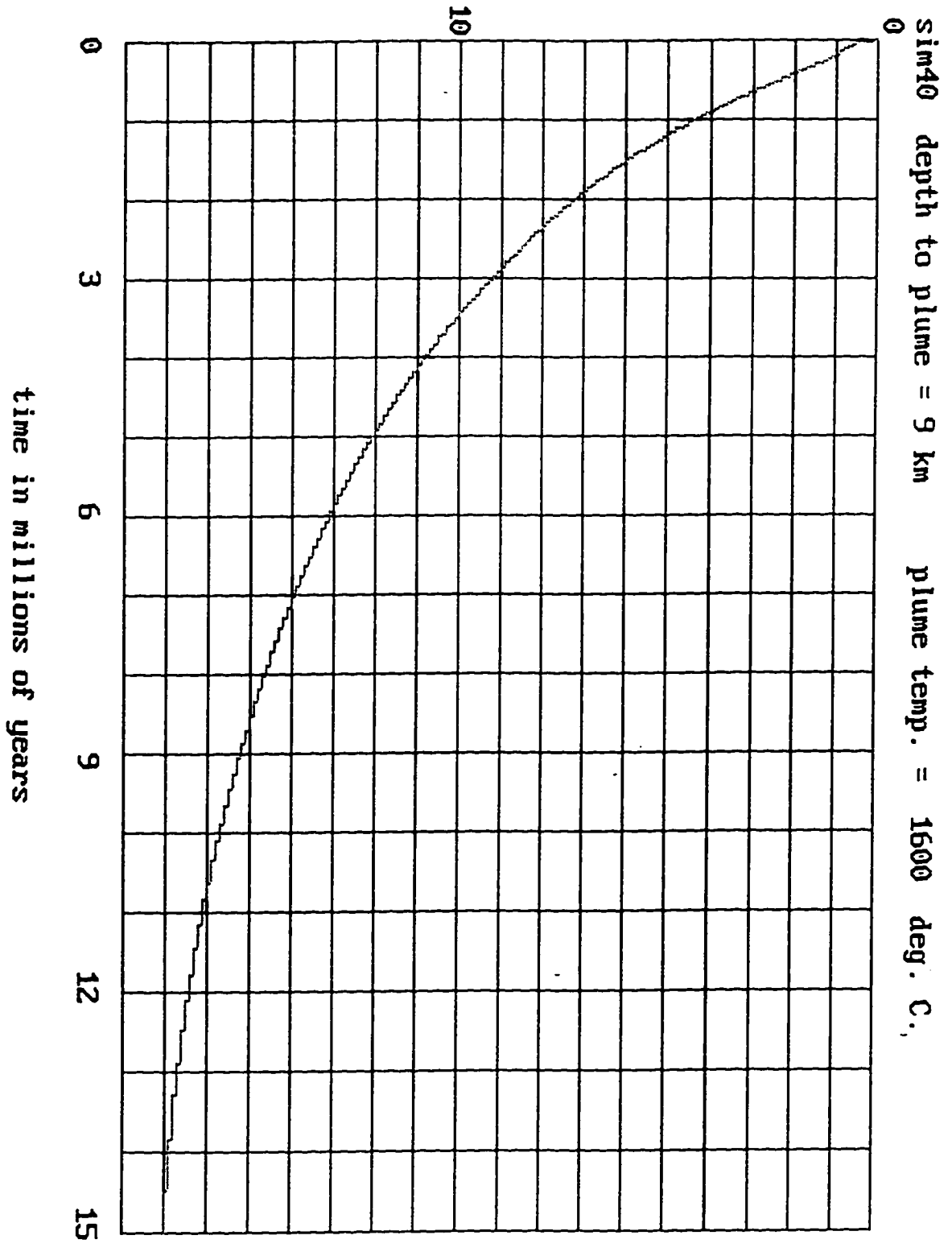




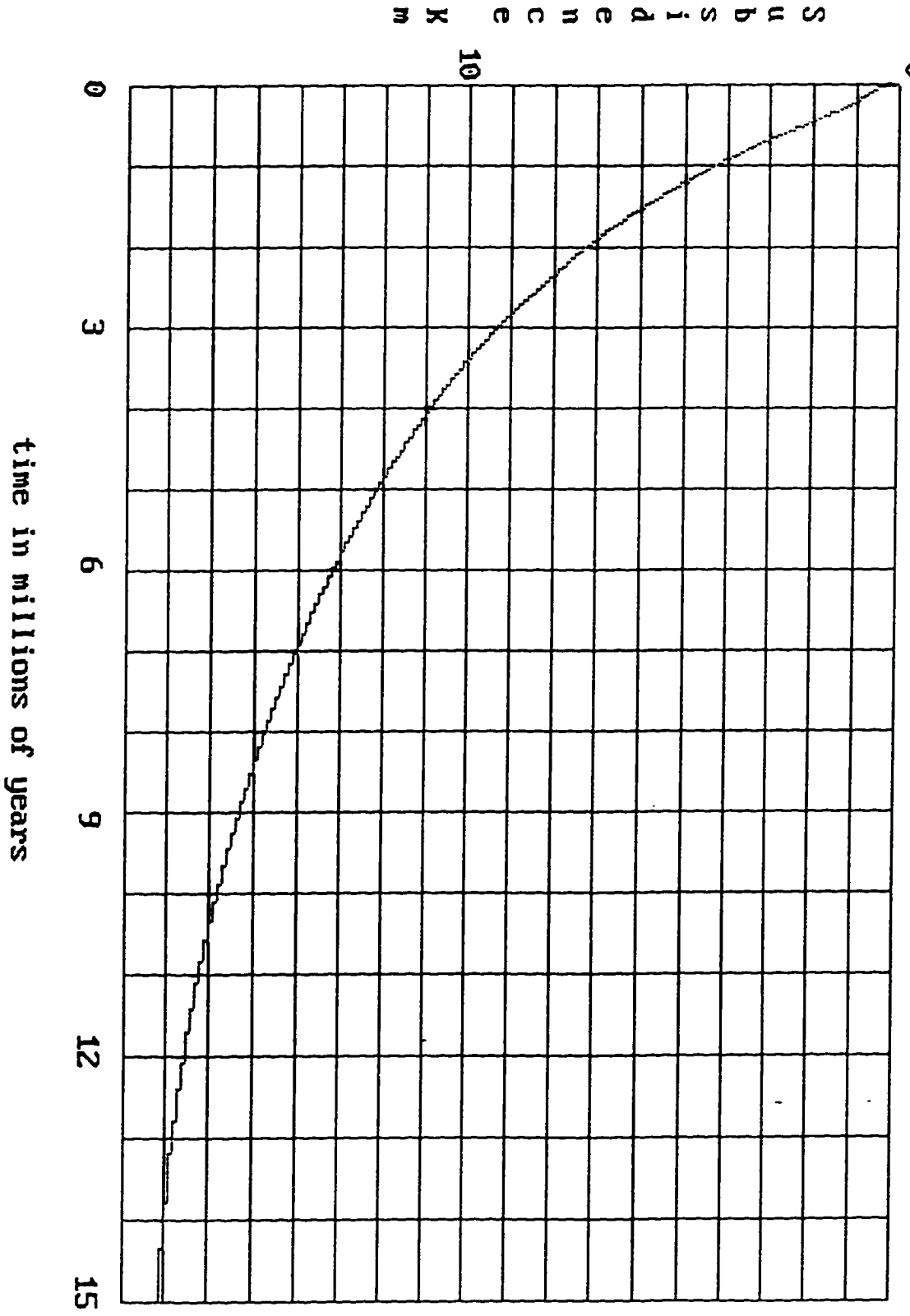




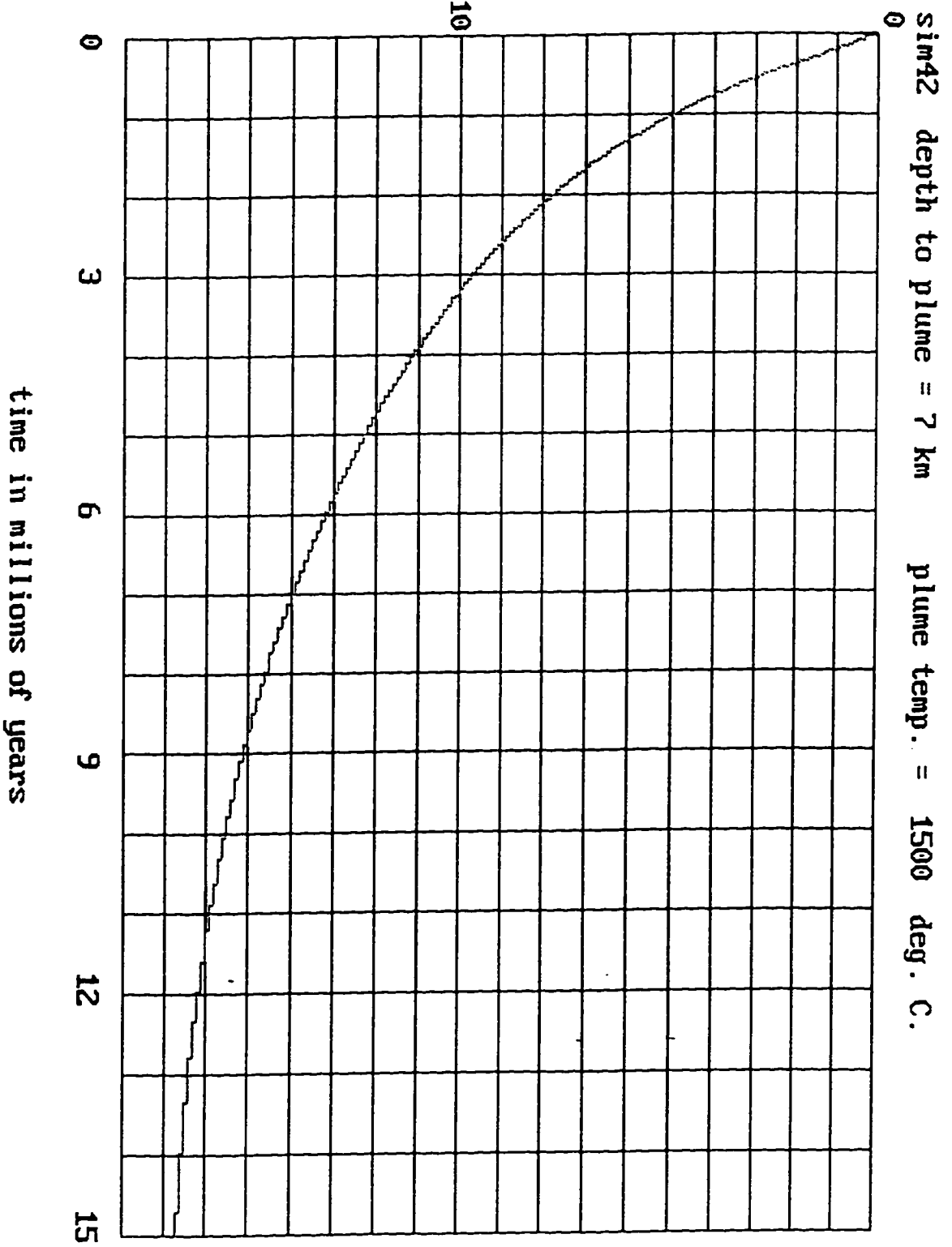
Subsidence Km



sim41 depth to plume = 9 km plume temp. = 1700 deg. C.

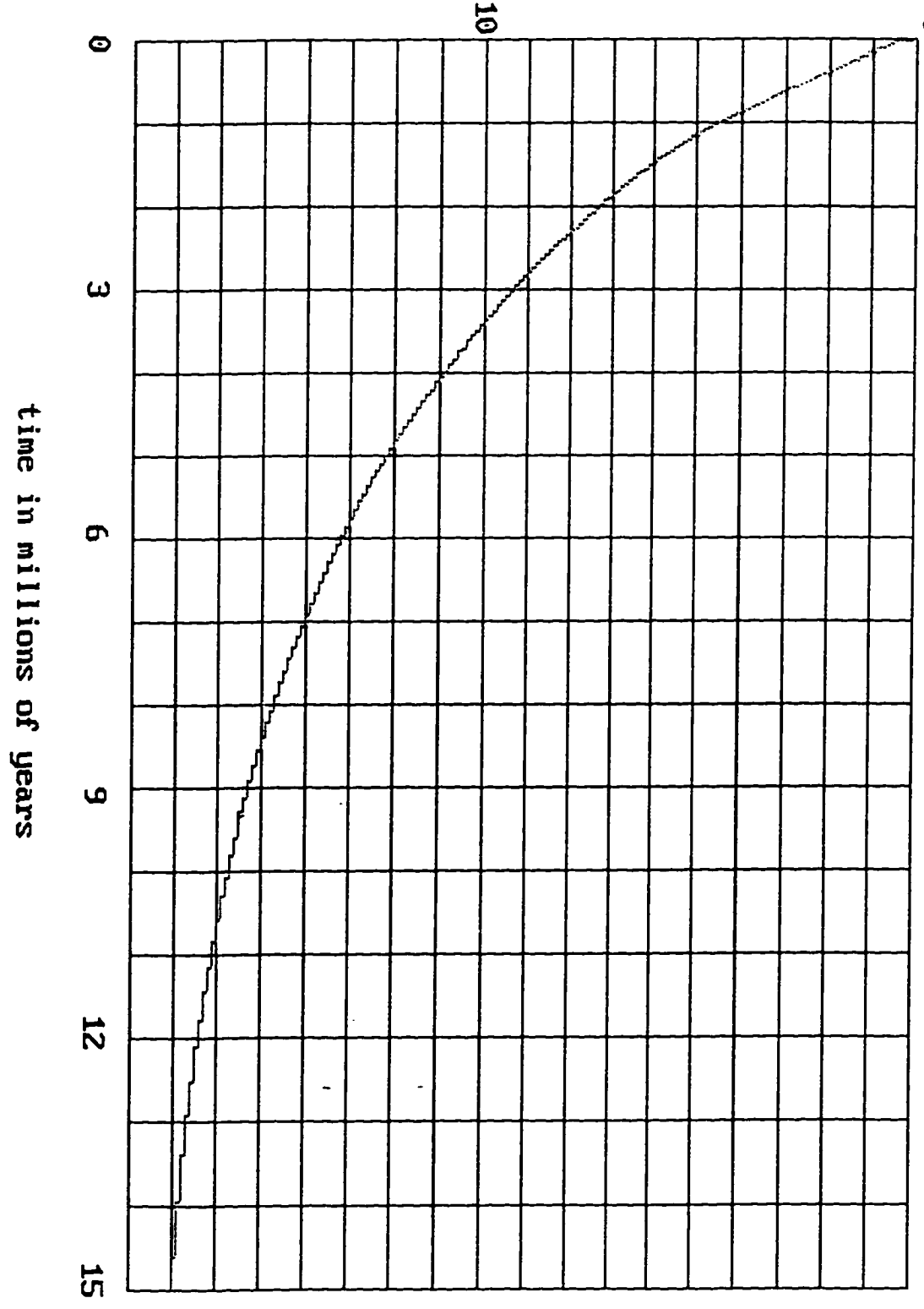


subsidence  
K m



Subsidence

sim49 depth to plume = 9 km plume temp. = 1500 deg. C.



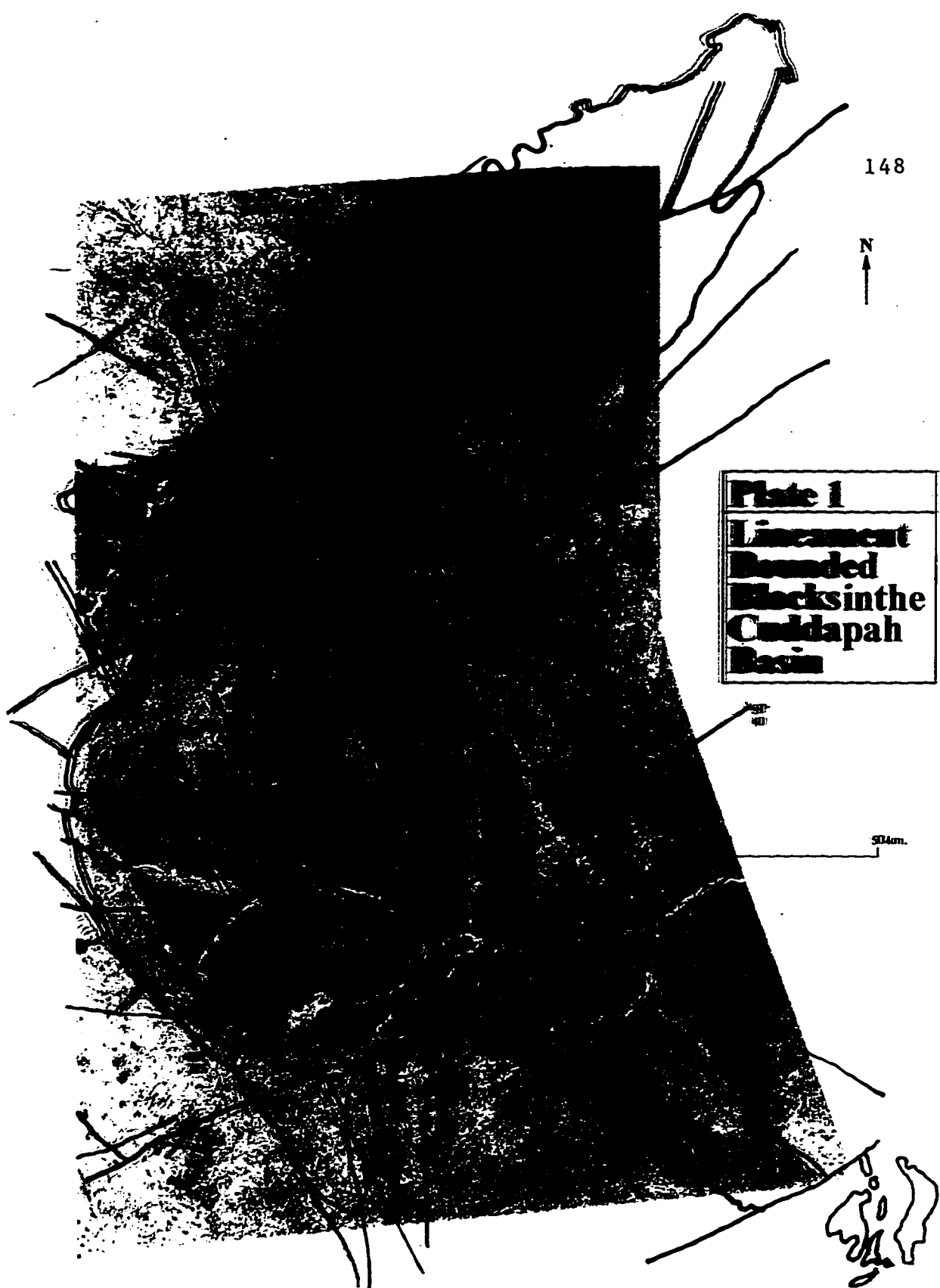
## **Appendix 4**

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**Plate 1**  
**Lineament**  
**Bounded**  
**Blocks in the**  
**Cuddapah**  
**Basin**

50km



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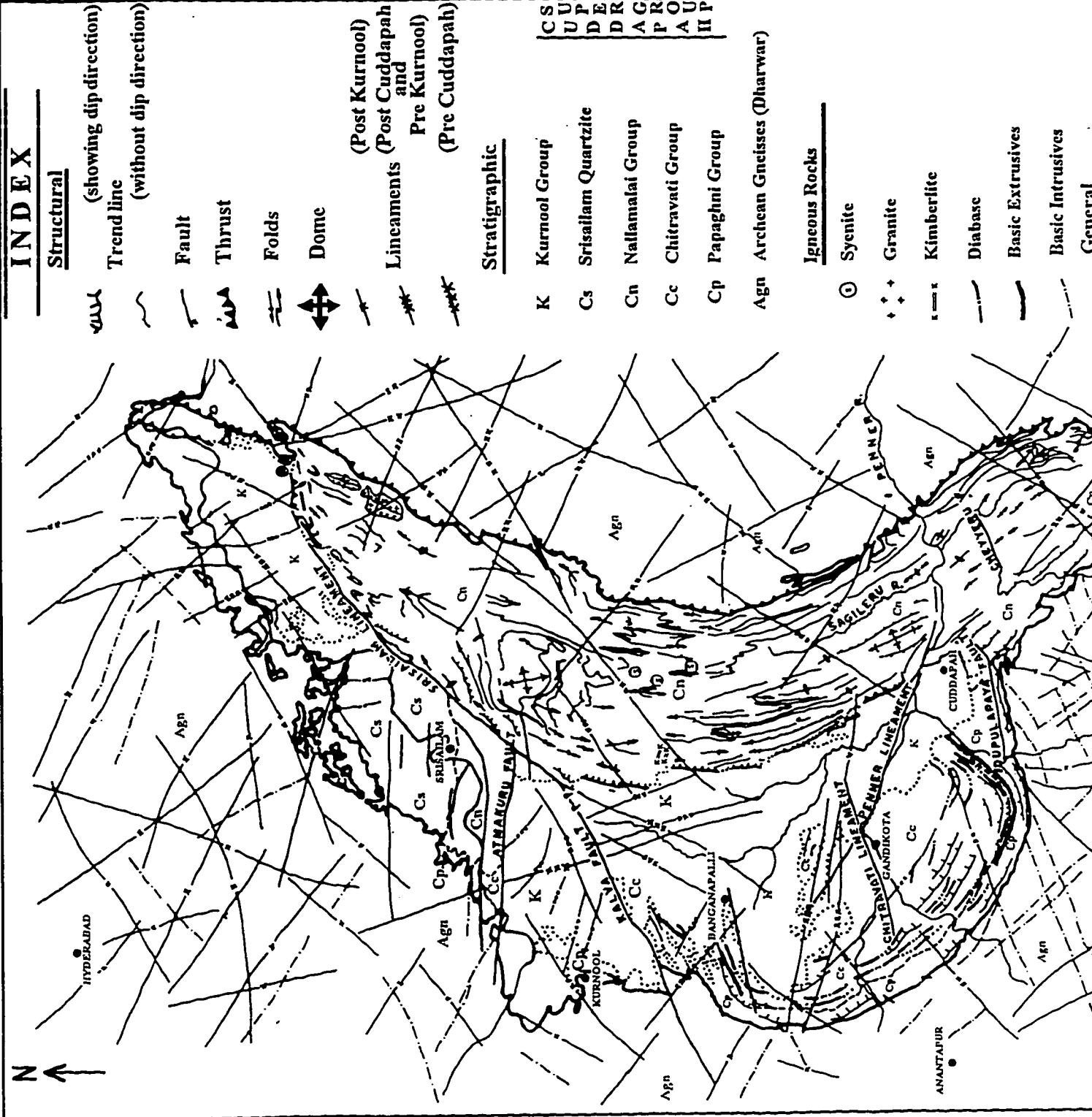
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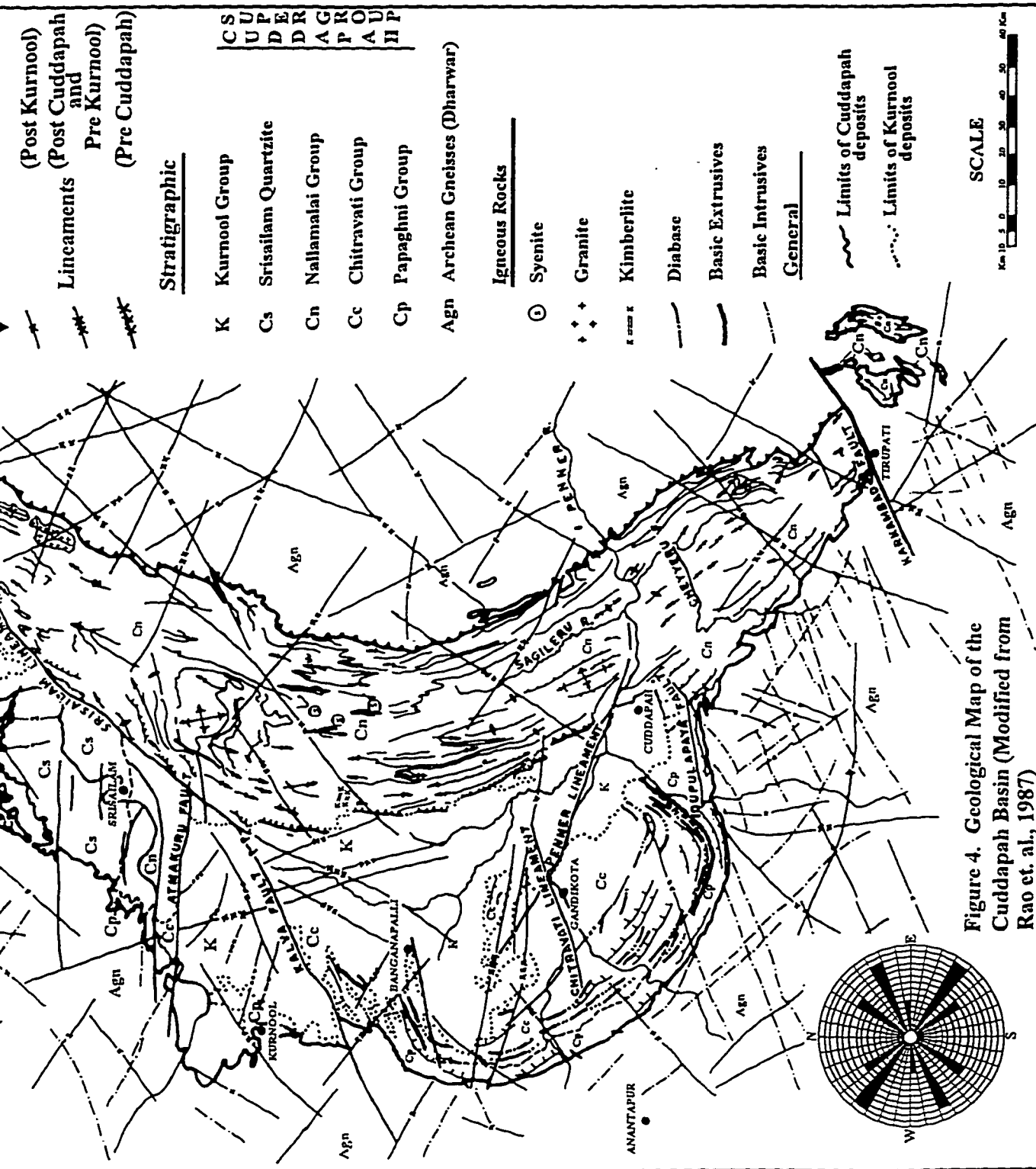






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Composite Lan  
Image of the  
Cuddapah Bas





Plate 1a  
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